

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

**NASA TECHNICAL  
MEMORANDUM**

**NASA TM X-71846**

**NASA TM X-71846**

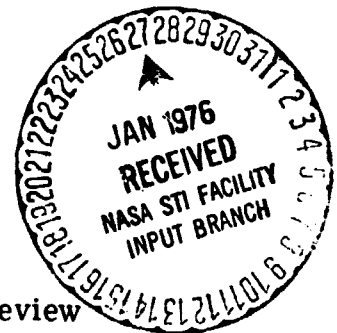
**(NASA-TM-X-71846) STATUS OF TECHNOLOGICAL  
ADVANCEMENTS FOR REDUCING AIRCRAFT GAS  
TURBINE ENGINE POLLUTANT EMISSIONS (NASA)  
50 p HC \$4.00 CSCL 21E**

**N76-15162**

**G3/07 08533  
Unclas**

**STATUS OF TECHNOLOGICAL ADVANCEMENTS FOR REDUCING  
AIRCRAFT GAS TURBINE ENGINE POLLUTANT EMISSIONS**

by Richard A. Rudey  
Lewis Research Center  
Cleveland, Ohio 44135  
December 1975



For inclusion in "THE RULES DOCKET" for the 1976 review  
of the EPA aircraft gas turbine engine emission standards

# STATUS OF TECHNOLOGICAL ADVANCEMENTS FOR REDUCING AIRCRAFT GAS TURBINE ENGINE POLLUTANT EMISSIONS

by Richard A. Rudey

Lewis Research Center

## ABSTRACT

Programs to develop and demonstrate the capability of advanced technology combustion systems to reduce the pollutant emissions of aircraft gas turbine engines currently in service have been underway, under the sponsorship of NASA, for approximately three years. These programs encompass a range of engines used in commercial and general aviation aircraft and have emission level goals consistent with the promulgated 1979 EPA standards. Although these programs are in various stages of completion, combustor test rig results indicate that substantial reductions from current emission levels of carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO<sub>x</sub>), and smoke are achievable by employing varying degrees of technological advancements in combustion systems. Minor to moderate modifications to existing conventional combustors produced significant reductions in CO and THC emissions at engine low power (idle/taxi) operating conditions but did not effectively reduce NO<sub>x</sub> at engine full power (takeoff) operating conditions. Staged combustion techniques were needed to simultaneously reduce the levels of all the emissions over the entire engine operating range (from idle to takeoff). Emission levels that approached or were below the requirements of the 1979 EPA standards were achieved with the staged combustion systems and in some cases with the minor to moderate modifications to existing conventional combustion systems. Verification of the test rig results in actual full-scale engines is still needed and will be obtained during a period from 1976 to 1977. In addition, other engine related criteria, such as performance, operational, and in-service factors must be considered before final engine emission level values can be quantified. Results from NASA sponsored and in-house conducted fundamental and applied research programs indicate that an entire new generation of combustor technology with extremely low emission levels may be possible in the future.

E-8576

# STATUS OF TECHNOLOGICAL ADVANCEMENTS FOR REDUCING AIRCRAFT GAS TURBINE ENGINE POLLUTANT EMISSIONS

by Richard A. Rudey

Lewis Research Center

## SUMMARY

Programs to develop and demonstrate the capability of advanced technology combustion systems to reduce the pollutant emissions of jet aircraft engines currently in-service have been underway, under the sponsorship of NASA, for approximately three years. These programs encompass a range of engines used as power plants for commercial and general aviation aircraft and have emission level goals consistent with established 1979 EPA standards. Five contracts, each using a specific engine for demonstrating the performance of advanced technology combustors, are currently proceeding with four engine manufacturers; Pratt & Whitney Aircraft, (P&WA), the General Electric Company (GE), the AiResearch Division of Garrett Corporation, and the Detroit-Diesel Allison (DDA) Division of General Motors. The engines selected for the technology demonstrations are the JT8D-17 and JT9D-7 of P&WA, the CF6-50 of GE, the TFE 731-2 of AiResearch, and the 501-D22A of DDA. Four of the contracts are phased type efforts starting out with concept screening tests in combustor test rigs and culminating with engine demonstration tests approximately three to four years after contract initiation. Engine tests are currently scheduled during a period from 1976 to 1977.

In addition to the engine related advanced technology programs, NASA is also sponsoring and conducting in-house experimental combustor studies and fundamental and applied research studies for evaluating the feasibility of advanced techniques, such as prevaporized/ premixed lean combustion schemes, to produce extremely low emissions with special emphasis placed on controlling the formation of oxides of nitrogen.

Combustor test rig results from the contract studies indicate that significant reductions from current levels of carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO<sub>x</sub>), and smoke are achievable by employing varying degrees of technological advancements in combustor systems. Relatively minor to moderate modifications to existing conventional combustors, such as changes in fuel atomization techniques and airflow distribution in the primary zone, produced significant reductions in the emission levels of CO and THC at engine low power (idle/taxi) operating conditions but only minor reductions (and in some cases increases) in NO<sub>x</sub> at simulated high power (takeoff) operating conditions. For several versions of JT8D-17, TFE 731-2, and 501-D22A modified engine combustors, these

E-8576

minor to moderate modifications reduced CO, THC, and smoke emission levels to values near or below the requirements of the 1979 EPA standards.

In order to achieve simultaneous reductions in all of the emissions, without employing water injection, staged combustion techniques were necessary. Staged techniques use two or more separate combustion zones which are independently optimized to control CO and THC at low power and NO<sub>x</sub> and smoke at high power. Combustor rig tests using the staged combustion techniques produced significant reductions in all the emissions over the entire simulated operating range of the JT8D-17, JT9D-7, and CF6-50 engines. The CO, THC, and smoke levels obtained approached or met the requirements of the 1979 EPA standards. The NO<sub>x</sub> levels, although somewhat higher than EPA standards, were reduced by 40 to 50 percent of current conventional engine combustor levels. Overall, the results indicate that the staged techniques can provide a major and substantial reduction in aircraft gas turbine engine emissions compared to current levels. Verification of the test rig results in actual full-scale engines is still needed and other engine related criteria, such as performance, operational, and in-service factors, must be considered before final values can be quantified. However, previous test rig to engine correlations indicate that the test rig results should be "representative" of final engine results.

The increased complexity of the staged combustion systems as compared to current conventional combustors will require a development effort of unknown difficulty at the present time. However, many of the factors of principal concern, such as the transition of combustion from one stage to the other, were successfully accomplished in combustor rig tests. The increased complexity of the staged systems indicates that their principal application would be for newly manufactured engines. Based on the combustor test rig experience and on fuel control studies, the application of staged combustion systems to newly manufactured production engines appears to be feasible within a reasonable development time period (3 to 5 years). The minor or moderate type modifications to conventional combustors are judged to be developable in a shorter length of time (2 to 3 years). These time estimates are in addition to, and are predicated on, successfully completing "proof-of-concept" tests in the demonstrator engines (currently scheduled for 1976 through 1977).

In evaluating the absolute level of emissions achieved with the advanced technology combustion systems, factors which influence the rate of formation of pollutants during the combustion process were considered. For NO<sub>x</sub> emissions, the most important factors are the combustor inlet temperature and pressure which are a function of engine cycle pressure ratio. The wide variance in cycle pressure ratio of the engines considered in the NASA/Industry contract programs produced appreciable differences in the attainable level of NO<sub>x</sub> emissions even though the emission control techniques employed were similar. Therefore, the impact of the combustion related factors must be considered when establishing NO<sub>x</sub> emission control levels for existing engines of wide varying cycle pressure ratios, e.g. JT8D-17 at 17tol, JT9D-7 at 21tol, and CF6-50 at 30tol. The possible implementation of even higher engine cycle pressure ratios for future

low energy consumption engines (possibly 40 to 50 to 1) will cause an even further variation in achievable  $\text{NO}_x$  emissions for a given level of combustor technology (conventional or advanced).

Results from fundamental and applied research studies indicate that an entire new generation of combustor technology with extremely low emission levels may be possible in the future. This technology will most likely employ prevaporized/premixed lean combustion schemes coupled with variable combustor geometry. Successful completion of conceptual design studies and subsequent testing of candidate concepts are needed before a timetable for the development of this level of advanced technology combustors can be established.

## INTRODUCTION

A wide ranging series of programs has been established by NASA to investigate the technological advancements needed to substantially reduce the levels of all pollutant emissions of current and future jet aircraft engines. The purpose of this report is to describe the progress that is being made in these programs and to: (1) relate the current state-of-the-art-technology for reducing current aircraft engine emissions to levels required by the promulgated EPA standards for 1979, and (2) describe related fundamental type combustion studies which indicate that a new generation of aircraft engine combustion systems with extremely low emission values may be developable in the future.

The Clean Air Act of 1970 charged the EPA with the responsibility to establish acceptable exhaust emission levels of carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen ( $\text{NO}_x$ ), and smoke for all types of aircraft engines. In response to this charge, the EPA promulgated the standards described in reference 1. Prior to the release of these standards, the aircraft engine industry, various independent research laboratories and universities, and the government were involved in the research and development of low emission gas turbine engine combustors. Some of this research was used as a guide to set the levels of the EPA standards. Several of the NASA programs underway at that time (mid 1973) are described in references 2 thru 4. The levels established in the standards and the first compliance date, Jan. 1, 1979, have acted as a catalyst for the timely development of advanced technology combustors. Two major NASA sponsored low emissions technology development programs, the Experimental Clean Combustor Program (ECCP) implemented six months prior to the issuance of the standards and the Pollution Reduction Technology Program (PRTTP) implemented within one year after the issuance date, have emission level goals consistent with the EPA standards. Most independent research and development (IR&D) programs in the industry are also using the EPA standards as goals for advanced technology developments.

Considerable success has already been achieved by industry to reduce the smoke of current jet aircraft engines. The principal technique used was to "lean-out" the combustor primary zone thus eliminating the "fuel-rich" combustion that produces carbon particle

formation, reference 5. Most of the current narrow body jet aircraft, B-727, B-737 and DC-9, engines have been retrofitted with low smoke combustors and the wide body jet aircraft, B-747, DC-10 and L-1011, engines entered service with low smoke combustors. One aspect of the engines used to power the wide body jets, e.g. the CF6 and JT9D engines, is that they operate on a higher pressure ratio cycle than the narrow body jet aircraft engines. This higher pressure ratio cycle has provided significant gains in reducing specific fuel consumption (SFC) but has resulted in higher levels of  $\text{NO}_x$  emissions. It has also led to smaller, higher heat release combustors which can have an adverse effect on the CO and THC emissions. Therefore, the principal goal in the research and development programs currently underway is to reduce the levels of the CO, THC, and  $\text{NO}_x$  emissions while still maintaining acceptable smoke emissions and without adversely effecting fuel consumption, durability, maintainability, and safety.

This report describes and discusses the results from some of the research and development programs being sponsored, directed, and/or conducted by NASA. Although this report will concentrate on NASA programs only, work supported by other government agencies (DOD, FAA, & EPA) and industry has provided considerable data on low emission advanced technology for aircraft gas turbine engine combustors. The results from the major NASA technology development programs, the ECCP and the PRTP, are presented and compared with the requirements of the 1979 EPA standards and an assessment of the development and engine application potential of selected advanced technology combustor concepts is given. Results from fundamental combustion studies are also described and the impact of these results on future jet aircraft engines is discussed.

## EMISSION REDUCTION TECHNOLOGY

The levels of gaseous emission pollutants vary with engine operating conditions, for most conventional combustors, in a manner illustrated in figure 1. The emission index (grams of pollutant/kilogram of fuel burned) levels of CO and THC are highest at the off-design operating conditions, such as low power idle, where combustion efficiency is at the lowest level. Conversely, the  $\text{NO}_x$  (normal practice is to express  $\text{NO}_x$  levels in terms of complete conversion to  $\text{NO}_2$ ) is the highest at the takeoff condition because combustion gas temperatures and pressures are at their highest levels. Because of this dependence on engine operating conditions, any emission control techniques that would have merit on an overall engine operating curve would certainly have to be most effective at these two extreme points, i.e. CO and THC must be drastically reduced at idle and  $\text{NO}_x$  at takeoff. Intermediate power points also contribute to the overall emissions hence they too must be considered but to a lesser degree. Although smoke is also a pollutant of concern, the following discussion deals only with the gaseous pollutants.

In considering the most attractive and effective techniques for

controlling these emissions, attention must be placed on the processes occurring in the primary combustion zone, figure 2. This schematic diagram describes the three principal zones of a conventional combustor: the diffuser where compressor discharge air is decelerated to low velocities needed for stable combustion; the primary zone where fuel and air are mixed and reacted to produce high combustion temperatures; and the secondary zone where additional air is added to complete combustion and reduce the temperature before the gases enter the turbine. Emission level control must occur within this basic combustion system structure.

The principal pollutants at idle power operation and their principal causes are listed in Table I. The low values of fuel nozzle pressure drop, fuel/air ratio, and combustor inlet pressure and temperature cause the mechanisms by which the pollutants are formed; poor fuel atomization and distribution in the primary zone, poor combustion stability, and quenching of the reactions before they are completed. All the corrective approaches listed refer to changes in the primary zone of the combustor with the exception of delaying the mixing of the secondary air. The principal pollutants and their causes during high power (takeoff) operation are listed on Table II. Combustor inlet temperature and pressure, and fuel/air ratio are all high which results in the high flame temperature which is the principal contributor to  $\text{NO}_x$  production. Excessive residence time is important because  $\text{NO}_x$  production is also a function of the time the free nitrogen and oxygen are exposed to the high temperatures, reference 6. All of the corrective approaches refer to actions required in the primary zone except for rapid quenching which would take place in the secondary zone.

In comparing the various corrective approaches needed to simultaneously reduce both the high and low power emissions, the dilemma shown in Table III becomes apparent. To effectively reduce all of the emissions simultaneously, over the entire engine operating range, will require the development of multiple staged combustors, wherein each stage (minimum of two) would be optimized to obtain maximum effectiveness in controlling either CO and THC or  $\text{NO}_x$ . The development of a variable geometry combustor that would allow the independent control of the corrective approaches as a function of engine operation would also be effective. Emission control techniques that use the corrective approaches listed in Table I and II are described below.

### Evaluation of Control Techniques

Fundamental studies. - Many techniques to reduce low power emissions have been evaluated by NASA including the use of air-assist fuel nozzles, airblast fuel nozzles, and fuel scheduling in the primary zone. Air-assist and airblast fuel nozzles use high pressure and high velocity air, respectively, to aid in atomizing the fuel and are very effective for reducing CO and THC at idle conditions, references 7 and 8. Fuel scheduling reduces the number of fuel



nozzles that are supplied with fuel thus resulting in improved atomization, reference 9.

Techniques to reduce high power emissions have concentrated on evaluating the effect of prevaporizing and premixing fuel and air prior to combustion using the "flame tube rig" at the NASA, Lewis Research Center which is shown schematically in figure 3. Gaseous propane or atomized Jet-A fuel is injected upstream of a perforated flame holder with sufficient distance to provide a completely prevaporized/premixed fuel/air mixture to the primary zone (flame zone) test section. A composite representation of results obtained from these "flame tube rig" tests is shown in figure 4. At the test conditions indicated, extremely low levels of  $\text{NO}_x$  emissions (E.I. < 1 g/kg) were obtained at very lean equivalence ratios,  $\phi$  (ratio of the fuel/air ratio to the stoichiometric fuel/air ratio). These low  $\text{NO}_x$  E.I. values were obtained at reasonable residence time (about 2 milliseconds) and at combustion efficiencies in excess of 99.7. This type of data is being used in an attempt to define minimum levels to which  $\text{NO}_x$  may be reduced by utilizing the lean prevaporized/premixed combustion technique. Therefore, the operating conditions for the experimental tests were very carefully controlled and do not necessarily duplicate conditions in an actual engine except for the levels of inlet pressure and temperature which simulate a supersonic cruise condition. Another factor which is important in evaluating these results is that at extremely lean equivalence ratios ( $\phi < 0.5$ ) combustion stability can be a problem because operation is near the lean flammability limit. Improved lean stability can be accomplished, in a fundamental sense, by using a small amount of gaseous hydrogen as described in reference 10. Other fundamental and applied research studies on prevaporized/premixed lean combustion are being conducted at the Jet Propulsion Laboratory and under the sponsorship of the NASA Lewis Research Center by the General Applied Sciences Laboratory (GASL), reference 11, and the Solar Division of International Harvester, reference 12.

The principal factor which controls  $\text{NO}_x$  formation in a combustion process is the flame temperature as illustrated in figure 5. Reductions in flame temperature are accomplished most efficiently by employing prevaporized/premixed lean combustion techniques. Extremely low flame temperatures and  $\text{NO}_x$  emissions can be obtained in prevaporized/premixed systems especially when using  $\text{H}_2$  enrichment as shown in figure 5. To a somewhat lesser degree, any form of lean combustion will provide the benefit of reducing flame temperature. Another effective technique for reducing flame temperature is to inject a diluent such as water into the combustion region. The reduction in  $\text{NO}_x$  obtained by injecting water into the primary zone of an experimental combustor is illustrated in figure 6. A reduction of approximately 75 percent in  $\text{NO}_x$  emission index was obtained with a water flow to fuel flow ratio of unity.

Other techniques to reduce  $\text{NO}_x$ , by increasing velocity and using rapid quenching to reduce residence time, have been investigated by NASA in experimental combustors.

Experimental combustors. - For the past five years, NASA has been evaluating several experimental combustors which incorporated a variety of the emission control techniques described in the preceding sections. The majority of the effort on the evaluation of low pollutant emission combustors conducted at the Lewis Research Center has been with the swirl-can-modular combustor which is described in detail in references 13 to 15. This combustor consists of a large number (80 to 120) of swirl can modules (each acting as a small, separate fuel/air mixer) arranged into a full annular array. A fuel/air mixture passes through a swirler which, in conjunction with a flame stabilizer, forms a small stable flame zone. The combination of a small flame zone and the partially premixed fuel/air provides for short residence times and some degree of flame temperature control. Typical  $\text{NO}_x$  emission results obtained with this type of combustor are compared with emission levels of typical conventional combustors in figure 7. Thirty to fifty percent reductions in  $\text{NO}_x$  emission index are indicated over the range of combustor inlet temperatures investigated (typical of present day aircraft gas turbine engines). The greatest difficulty in the development of this combustor concept has been the inability to simultaneously reduce low power emissions of CO and THC and high power emissions of  $\text{NO}_x$ . Low values of CO and THC have been achieved by using specialized module designs and by employing fuel scheduling but these modifications were not successfully coupled with low  $\text{NO}_x$  designs to provide an integrated combustor for low emissions at all operating conditions.

Other types of NASA experimental combustors have also been evaluated to explore their pollutant reduction potential. A double annular combustor, reference 16, has been used to study the effects of fuel scheduling and air velocity control on CO and THC at low power. The impact of air velocity on  $\text{NO}_x$  formation was also studied with this combustor. Also, an in-house project has recently been initiated at the Lewis Research Center to evaluate many of the control techniques as applied to small gas turbine engine combustors that would have application to helicopter and small general aviation class engines.

### Technology Development and Application

The development and application of various pollutant emission control techniques to in-service aircraft gas turbine engine combustors are being investigated in two large NASA/Industry contract programs. The primary goal of these programs is to evaluate the emission reduction potential and the development problems that are associated with translating emission control techniques into advanced technology combustors for existing engines. The control techniques that are being emphasized use the advanced technology approach (combustor design changes) rather than the use of operational (increased compressor bleed) and/or functional (water injection) approaches. The two programs include a wide variety of engines that are representative of those included in the promulgated 1979 EPA emission standards.

Experimental Clean Combustor Program. - The Experimental Clean Combustor Program (ECCP), was initiated in December 1972 with the objective to develop and demonstrate, in a full-scale engine, advanced technology combustors that are capable of reducing pollutant emissions in the large high bypass ratio engines (EPA Class T2, thrust over 8,000 lbs.) that power the wide body jets. The original emission level goals were established from NASA studies and were subsequently adjusted to be consistent with the EPA Standards published in mid 1973. The two contractors that were selected, and are currently under contract, are Pratt & Whitney Aircraft (JT9D-7 engine) and the General Electric Company (CF6-50 engine). The program is a three-phased effort scheduled to culminate in engine demonstration tests in 1976. Testing in Phase I (screening of a multitude of low emission concepts) and Phase II (refinement for engine adaptation) has been completed by General Electric. Pratt & Whitney has completed the Phase I tests and Phase II testing is nearly complete. Both contractors are under contract and are in the preliminary stages of Phase III. A complete description of the ECCP is given in reference 17.

The two advanced technology CF6-50 engine combustor concepts that were evaluated in Phase II are shown along with the conventional CF6-50 engine combustor in figure 8. Both designs utilize a form of fuel scheduling (staged combustion) for reducing pollutant emissions over the entire engine operating range. The pilot stages of both the radial/axial staged and the double annular are optimized for high efficiency (low CO and THC emissions) at engine low power (idle) and the main stages are optimized for lean combustion (low  $\text{NO}_x$ ) at full power (take-off). Various combinations of fuel staging can be used for off-design operation such as approach power settings. The radial/axial staged configuration utilizes a premixed fuel/air technique in the main stage whereas the double annular configuration uses an airblast fuel nozzle and airflow control in the main stage. These two concepts employ four of the previously discussed control techniques: (1) fuel scheduling; (2) airblast fuel nozzles; (3) lean mixture combustion; and (4) premixing. Based on the results of Phase II testing, the double annular concept was chosen for the Phase III engine demonstration tests. All of the testing in Phases I and II were performed in a full annular combustor test rig which closely duplicates the flow path of the CF6-50 engine. All engine inlet and exit operating conditions were simulated except for combustor inlet pressure which was limited to a maximum of 10 atmospheres. Further details are given in reference 18.

The two advanced technology JT9D-7 engine combustor concepts that are being evaluated in Phase II are shown schematically along with the conventional JT9D-7 engine combustor in figure 9. As with the CF6-50 concepts, both designs use fuel scheduling (staging) as the principal approach to controlling overall pollutant emissions. The hybrid concept utilizes a parallel (radial) fuel staging approach which includes a premix technique in the pilot stage and a variation of the swirl can concept in the main stage. This configuration is an attempt to mate the lowest CO and THC emission design (premix pilot stage) and the lowest  $\text{NO}_x$  emission design (swirl-can-module stage) that was tested in Phase I, see reference 19. The vorbix configuration utilizes a series-type (axial) fuel staging approach with standard

pressure atomizing fuel nozzles in both the pilot and main stages. High intensity swirlers are located immediately downstream of the main stage fuel injection point to promote very intense, rapid mixing of the fuel and air in the flame zone. The combination of the intense mixing and hot gases exiting from the pilot stage allows lean combustion in the main stage and also reduces residence time due to quick quenching of the hot gases. These concepts also employ four control techniques: (1) fuel scheduling; (2) lean mixture combustion; (3) premixing; and (4) quick quenching. Based on the testing performed to date in Phase II, the vorbix concept has been selected for the Phase III engine demonstration tests. All of the testing in Phases I and II was conducted in a 90 degree sector test rig which closely duplicated the JT9D-7 engine flow path. Again, all operating conditions except inlet pressure, which was limited to approximately 6 atmospheres, were simulated. Further details are given in reference 18.

Pollution Reduction Technology Program. - The second major program that has been implemented to evaluate the application potential of emission control techniques is the Pollution Reduction Technology Program (P RTP). The P RTP was initiated in mid-1974 as an effort to develop advanced technology combustors to reduce pollutant emissions for three classes of engines included in the 1979 EPA Standards that were not considered in the ECCP. The contractors and the respective engines selected for the P RTP are Pratt & Whitney Aircraft, JT8D-17 (EPA Class T4), the AiResearch, TFE 731-2 (EPA Class T1), and the Detroit-Dieser Allison, 501-D22A (EPA Class P2). The advanced technology combustor evaluations are being conducted in a multiphase approach similar to the ECCP with engine demonstrations scheduled in 1976 and 1977. Phase I (concept screening tests) is underway with all three contractors and preparations are being made to implement Phase II with two contractors. Program goals were established to be consistent with published 1979 EPA standards.

The advanced technology combustor concepts selected for the Phase I screening tests are shown in figures 10, 11, 12 for the JT8D-17, TFE 731-2, and 501-D22A engines, respectively. The advanced technology combustor concepts were selected based on a trade-off between estimated degree of emission reduction potential and development risk. In all cases, the selected configurations representing the least development risk (A or B) have the least likelihood of achieving all of the pollutant emission goals. The B, C or D configurations represent a higher development risk but provide a better potential for achieving or exceeding the pollutant emission reduction goals.

The JT8D-17 Phase I concepts are being tested with air-assist fuel nozzles, airblast fuel nozzles, fuel scheduling (staging), lean combustion, and premixing control techniques. The TFE 731-2 Phase I concepts use all of the above techniques and the modified baseline combustor is also being tested to document the effects of increased compressor discharge bleed and water injection. The 501-D22A Phase I concepts use similar techniques to those described for the JT8D-17. Although all the engine programs use similar types of control techniques, the applications of these techniques to the individual engines vary. For example, the TFE 731-2 concept C uses parallel or radial fuel staging whereas the 501-D22A concept D uses series or

axial fuel staging as does the JT8D-17 concepts B and C. Other differences of note are that the JT8D-17 and 501D-22A are can-annular combustors whereas the TFE 731-2 is a full annular design and that the TFE 731-2 is a reverse flow design versus the axial flow types of the JT8D-17, 501-D22A and JT9D-7 and CF6-50 of the ECCP.

The essential point is that although the pollutant control techniques are similar for all of these advanced technology combustors, the methods for applying the techniques to actual engine constrained designs must be and is being varied as the individual engine configuration dictates. The degree of success of any one application will not only be dependent upon the control techniques used but to a great degree will also depend upon the ability and ingenuity of the engineer to adapt these techniques to the engines' specific characteristics. The wide variation of techniques and applications being evaluated in the ECCP and the P RTP is providing a large data bank of low emission, advanced technology combustor design and development information.

Future programs. - NASA is planning to implement future programs to study the application of more advanced technology, e.g. the Lean Burning Variable Geometry (LBVG) concept, to future generation jet aircraft engines. Before these programs can be initiated, more fundamental data are needed in the areas of prevaporizing and premixing fuel and air, autoignition and flashback constraints on the premixed fuel and air, and variable geometry concepts and control techniques. A concentrated effort to develop a comprehensive design criteria data bank is being initiated by the Lewis Research Center to provide the needed information. After the attainment of the necessary design data, a multi-phased program similar to the ECCP is anticipated. The emission level goals of future programs will be responsive to both the published EPA standards for low altitude (<3000 feet) operation and to the recommendations of the Climatic Impact Assessment Program study, reference 20, for high altitude cruise  $\text{NO}_x$ . The availability of this level of advanced technology will not likely be available for implementation in current jet aircraft engines. A new generation of jet engines would be the beneficiary and the time of useful application will likely be in the late 1980's.

## STATUS AND RESULTS

The status and results obtained to date in the technology development and application programs (principally the ECCP and P RTP) are discussed in this section.

## Program Status

A milestone schedule giving the current status of the various contracts is presented in figure 13.

Experimental Clean Combustor Program. - Both of the Phase II efforts are nearly completed as indicated and both Phase III efforts have been initiated. All Phase II testing has been completed at GE and final optimization tests of the selected vorbix concept is underway at P&WA. The initial effort in Phase III is concentrating on the design and fabrication of the engine/combustor hardware, the breadboard fuel control system, and the exhaust gas measurement system. Engine tests of the selected combustor concepts, double annular for the CF6-50 and the vorbix for the JT9D-7, are scheduled to begin in mid 1976 and be completed before the end of 1976. Final contractor reports describing and discussing the results of the Phase I combustor rig tests have been completed, references 19 and 21. Phase II contractor reports are scheduled for completion in early 1976.

Pollution Reduction Technology Program. - Combustor rig tests of all the advanced technology combustor concepts is underway in Phase I for all three contractors. Screening of various modifications to the first two concepts (A & B, figure 10) has been completed for the JT8D-17 engine. Testing of concept C is underway and will be completed in late 1975. The JT8D-17 engine combustor work will be terminated at the end of Phase I. Screening of various modifications to all three concepts (figures 11 and 12) of both the TFE 731-2 and 501-D22A engines are underway and the testing will be completed in early 1976. Preparations for the Phase II efforts are underway and Phase II is scheduled to begin at both AiResearch and DDA in early 1976. Several preliminary engine and/or integrated combustor/turbine tests of a selected Phase II concept are being considered at both AiResearch and DDA in an attempt to identify significant development problems and to verify and correlate emissions data between the test rigs and full-scale engines. Otherwise, planned engine demonstration tests are scheduled for 1977 at both AiResearch and DDA.

Future Programs. - The fundamental studies, e.g. flame tube rig tests, that are currently underway will continue through the next several years. Calendar year 1979 has been set as a target date for establishing the design data bank to be used for conceptual design studies of the Lean Burning Variable Geometry (LBVG) combustion scheme. Successful completion of the conceptual design studies and subsequent testing of candidate concepts will establish the timetable for the development of this level of advanced technology combustors.

### Experimental Clean Combustor Program

The emissions and related performance results obtained to date for a selected "best" configuration of each of the advanced technology combustor concepts shown on figures 8 and 9, are summarized and compared to the baseline engine combustors in Tables IV through VII. All of the emission index (E.I.) values listed on Tables IV and VI are computed to be those that would occur at combustor operating conditions consistent with actual engine operation. To perform this computation, combustor test rig data, which was limited to 6 to 10 atmospheres pressure, was extrapolated to engine related pressure and correlated for appropriate values of reference velocity, fuel/air ratio, and inlet temperature using the procedure described in reference 18.

The computation of the listed Environmental Protection Agency Parameter (EPAP) values is consistent with the recommended procedure from reference 1, where EPAP is defined as:

$$\text{EPAP} = \text{lbs of pollutant/1000 lbs thrust-hours/cycle}$$

(1)

Details of the EPAP calculations using equation 1 are given in reference 18.

CF6-50 Engine. - Table IV presents the emissions in terms of E.I.'s at the various operating conditions that are used in the landing takeoff (LTO) cycle computation and the resultant EPAP values. Also included are the representative E.I.'s obtained at simulated altitude cruise conditions (35,000 feet, Mach 0.8). The selected "best" concept configurations, double annular, D/A-13, and radial/axial, R/A-2, (see reference 18 for definitions), were chosen from all of the configurations tested in Phase II based on the following factors: (1) the lowest combined emission levels obtained at all of the engine operating conditions; (2) acceptable performance in terms of pressure drop, combustion efficiency, and exit temperature pattern factor; and (3) acceptable staging characteristics at the approach condition. Development potential in terms of durability, operational stability, altitude relight capability, and overall engine/control integration were also considered.

Many of the double annular and the radial/axial configurations achieved emission levels nearly equal to and in some instances less than those shown in Table IV and a complete listing of all of the Phase II test results is given in reference 18. Nevertheless, D/A-13 and R/A-2 were judged to be the best overall based on the selection factors used.

Comparison of the EPAP values achieved with D/A-13 and R/A-2 and the baseline engine combustor shows that significant reductions in all emission levels were achieved. Smoke levels are not listed because

the values for all the combustors were well below the requirements established in the EPA standards. The D/A-13 configuration was capable of reducing the CO and THC emissions to levels equal to or less than those required to comply with the EPA standards. A  $\text{NO}_x$  EPAP value of 4.15 was obtained with D/A-13 compared to the 3.0 required by the standards. Although not meeting the EPA standards, the 4.15 value represents a 45 percent reduction from the current baseline level. The reduction in  $\text{NO}_x$  E.I. at high power (takeoff) conditions was greater than 50 percent of the baseline value. The lesser percentage reduction in EPAP that was obtained can be explained by comparing the E.I.'s at approach. An increase in approach  $\text{NO}_x$  was obtained using the D/A-13 configuration as compared to the baseline combustor. This increase is caused by higher flame temperatures produced by higher fuel/air ratios needed when operating the pilot only during approach. The R/A-2 configuration also made significant reductions but was not capable of reducing any of the gaseous emissions to the levels required by the EPA standards.

From an emissions and performance (see Table V) viewpoint, the double annular and the radial/axial concepts represent major steps for reducing engine emissions without compromising performance. The  $\text{NO}_x$  levels shown for the double annular concept are judged to be nearly optimum for the level of advanced technology evaluated.

JT9D-7 Engine. - Table VI presents the emission level results obtained for the two selected concept configurations, vorbix, S-20, and hybrid, H-6 (see reference 18 for definition), tested in Phase II. The factors used in selecting these two configurations were the same as those previously discussed in relation to the CF6-50 engine configurations. Comparison of results with baseline engine emissions shows that considerable reductions in all emission levels were obtained in terms of both EPAP and E.I. at specific operating points. As with the CF6-50 configurations, smoke levels were acceptably below the EPA standards and are therefore not listed.

The S-20 configuration achieved THC emission levels below the EPA standards but only approached the required values for both the CO and  $\text{NO}_x$ . Using the unbled idle condition (recommended for the low power condition based on P&WA's interpretation of the EPA LTO cycle, see reference 18), the CO reduction in EPAP was approximately 60 percent compared to the 70 percent required by the EPA standards. Further reductions in CO may be obtainable with this configuration and will be explored during the Phase II optimization tests. The  $\text{NO}_x$  EPAP was reduced approximately 30 percent below the baseline value as compared to the 40 percent reduction required to comply with the EPA standards. Although some further improvement in  $\text{NO}_x$  level might be achieved during the planned Phase II optimization tests, it is unlikely that the reductions will be sufficient to meet the EPA standards. The  $\text{NO}_x$  E.I. levels at full power (takeoff) were reduced by close to 50 percent of the baseline value, but again, the inability to achieve appreciable reductions at approach (result of fuel staging between the pilot and main stages) resulted in the lesser percentage improvement in the computed EPAP. The H-6 configuration was able to reduce both the CO and THC emissions to levels near or below the EPA standards.  $\text{NO}_x$  emission levels were comparable to those obtained with the S-20 configuration.



From an emissions and performance (see Table VII) viewpoint, both the vorbix and the hybrid configurations exhibited the capability to significantly reduce engine emissions with varying degrees of success in meeting the requirements of the EPA standards without adversely affecting performance.

ECCP Summary. - In general, at this point in the ECCP, all of the advanced technology combustor concepts have exhibited the potential for significantly reducing the exhaust emissions of the two demonstrator engines. Combustor rig tests of the "best" configurations (D/A-13 and R/A-2) produced emission levels (corrected to engine conditions) that approached or were below the EPA standards for CO, THC, and smoke. Significant reductions in NO<sub>x</sub> were also obtained but were not sufficient to meet the EPA standards. Continued development of the R/A-2 and S-20 configurations may provide further decreases in CO emissions but is unlikely to appreciably reduce the levels of NO<sub>x</sub> emissions achieved to date without adversely affecting performance. Therefore, the advanced technology combustor concepts that are being developed for the CF6-50 and JT9D-7 engines will not be capable of reducing the NO<sub>x</sub> to the EPAP of 3.0 required by the EPA standards.

Acceptable performance in terms of combustor efficiency, pressure drop, and pattern factor (although higher than baseline values, pattern factor should be capable of reduction through development) were also obtained as related to engine conditions. Other factors that have been or are being evaluated in Phase II, such as altitude relight, fuel staging and control system design, coking, carboning, and liner cooling, all appear to be within developable limits. The ability of the staged concepts to perform all of the normal engine operational functions will not be known until the actual Phase III engine demonstration tests are performed. However, the results at this time do not indicate that major problems are to be expected. Verification of emission levels in the actual engine environment is still needed but past experience, correlations between test rigs and engine data, indicates that the data presented in Table IV and VI should be representative of expected engine values.

In addition to the emission reductions obtained for the LTO cycle, reductions of up to a factor of 2 in NO<sub>x</sub> E.I. at simulated subsonic cruise conditions (Tables IV and VI) were also obtained. This reduction, although not achieving the factor of 6 reduction recommended by the CIAP study, would still represent a meaningful benefit for reducing the possible adverse impact of jet aircraft cruise NO<sub>x</sub> on upper atmosphere ozone.

Based on a consideration of the emission reductions, performance, and operational characteristics, optimized configurations of the double annular and the vorbix concepts will be used in the Phase III engine demonstrations for the CF6-50 and JT9D-7 engines, respectively. The radial/axial concept has significant deficiencies in staging characteristics and combustion stability and the hybrid concept has significant deficiencies in altitude relight. These two concepts would still require an unknown amount of development before they could be considered for engine demonstrations.

## Pollution Reduction Technology Program

The emissions and related performance results obtained from selected configurations of each of the advanced technology combustor concepts shown on figures 10, 11, and 12, are summarized and compared to the respective baseline engine combustors in Tables VIII through XIII. As in the ECCP, all values listed on Tables VIII, X, and XII are corrected to actual engine operating conditions. No extrapolation of test rig data was necessary for the JT8D-17 and 501-D22A combustors because the test rigs could duplicate engine levels of pressure, inlet temperature, and reference velocity. For the TFE 731-2 combustors, the test rig data were extrapolated using procedures similar to those described in reference 18. The computation of EPAP values is consistent with the procedure outlined in reference 1 using the engine manufacturers recommended operating conditions for the low power idle setting. Since the Phase I screening tests have not been completed, the results shown are for the "best" concept configurations that have been tested to date. The selection of the "best" configuration was based on the factors previously described in the ECCP discussion.

JT8D-17 Engine. - Table VIII gives the emission levels obtained during Phase I combustor rig tests with the "best" JT8D-17 engine configurations for both individual E.I.'s and computed EPAP's. Also shown are representative subsonic cruise (35,000 feet, Mach 0.8) E.I.'s for the engine baseline combustor and the vorbix concept. Since smoke is a more critical factor for this engine class (just recently involved in a low smoke combustor retrofit program), SAE smoke number values are listed for the high power conditions. The "lean front end" baseline combustor modification (replacing the pressure atomizing nozzle with an aerating type nozzle and adjusting primary zone airflow) was capable of reducing the levels of all the emissions including smoke but was not able to achieve the levels required by the EPA standards. The reductions in CO and THC EPAP closely approach the required levels whereas only a minor reduction in  $\text{NO}_x$  was achieved. Smoke was substantially reduced. Since this concept does not employ staged combustion (figure 10A), the approach power point did not adversely effect the EPAP value for  $\text{NO}_x$ . It is unlikely that such "minor" type modifications to the baseline combustor will provide sufficient enough reductions to achieve the EPA standards for CO, THC and  $\text{NO}_x$ . However, the reductions in CO, THC, and smoke are substantial. Cruise  $\text{NO}_x$  emissions were not measured but would be expected to be the same as the baseline combustor since the high power  $\text{NO}_x$  E.I.'s were not affected.

The vorbix concept (figure 10B) produced substantial reductions in all of the gaseous emissions while maintaining smoke levels comparable to the baseline combustor. The EPAP value of THC emissions was below the EPA standard requirement but the CO and  $\text{NO}_x$  values were higher than required. Both the CO and  $\text{NO}_x$  were reduced to approximately 50 percent of the baseline combustor EPAP value. This percentage reduction in  $\text{NO}_x$  was the best of any of the combustors tested in the ECCP or P RTP. The vorbix concept can also provide a potential 30 percent reduction in cruise  $\text{NO}_x$ .

Overall, the vorbix concept represents a major technological

advancement for the JT8D-17 engine combustor with the potential for significantly reducing all of the gaseous emissions (CO, THC and NO<sub>x</sub>) and still maintaining acceptable performance (Table IX). Additional development is still needed to achieve acceptable exit temperature pattern factors. The "lean front end" modification to the baseline combustor also provides substantial reductions in CO, THC, and smoke but no appreciable benefit in NO<sub>x</sub> emissions. Both of the concepts have altitude relight deficiencies which must be improved through further development. The staged premix combustor concept (figure 9C) has just entered the testing phase and results are too preliminary to evaluate.

TFE 731-2 Engine. - Table X presents the emission levels obtained during the Phase I combustor rig tests of the "best" TFE 731-2 configuration tested to date. Most of the data taken to date in this program has been at the two extreme operating points, idle and takeoff, hence very little EPAP data is available. Also the concept screening tests in this program are in an early phase of activity, see figure 13. Nevertheless, both modifications to the baseline combustor (figure 11A) and the piloted-airblast (figure 11B) concepts have produced substantial reductions in CO and THC emissions. The computed EPAP values (interpolated from the data obtained at the idle and takeoff operating conditions) approached or were below the levels required by the EPA standards. A small reduction in NO<sub>x</sub> was also obtained with the piloted-airblast concept as compared to the baseline combustor. Further reductions in NO<sub>x</sub> as well as lower values for CO and THC should be obtainable with subsequent modifications to the piloted-airblast concept. The use of both compressor bleed (10 percent) and an air-assist fuel nozzle were needed to achieve the low CO and THC emissions obtained with the modified baseline combustor. Smoke was acceptable for all the concepts tested and was virtually non-existent for the piloted-airblast concept. No data from the piloted premix/prevaporization concept (figure 11C) are available at the present time, however, if it is successful, it should provide the best possibility for achieving significant reductions in NO<sub>x</sub>. No cruise data are currently available. Performance characteristics of all the concepts tested (Table XI) are judged to be acceptable with some development still required in exit temperature pattern factor.

501-D22A Engine. - Table XII presents the emission levels obtained during the Phase I combustor rig tests of the "best" 501-D22A configurations tested to date. A substantial amount of test data has been obtained from all three advanced concepts shown in figure 12 at all LTO operating conditions. All of the "best" configurations selected were capable of controlling all of the emissions to values below the levels required by the EPA standards. In the case of CO, THC, and smoke emissions this required substantial reductions, however, NO<sub>x</sub> emission level actually increased compared to the baseline combustor. Further development of the prechamber and staged fuel concepts should provide some reduction in the NO<sub>x</sub> levels. No cruise data was taken with these concepts. The performance characteristics of all the configurations (Table XIII) were acceptable and the measured exit temperature pattern factors were better than the baseline combustor.

PRTP Summary. - At this point in the PRTP, all of the advanced technology combustor concepts tested have exhibited the potential for substantially reducing the exhaust emissions of the three demonstrator engines selected for the program. In the case of the 501-D22A engine, the selected "best" configurations exhibited the capability of meeting all of the emission levels required by the EPA standards. This was possible only because this engine has a very low engine cycle pressure ratio and, subsequently, low baseline  $\text{NO}_x$  emissions compared to the EPA standards. Therefore, an increase in  $\text{NO}_x$  emissions was allowable. The other two engines, JT8D-17 and TFE 731-2, require substantial decreases in  $\text{NO}_x$  to meet the EPA standards and as a result, even though substantial reductions were obtained with the advanced technology combustor concepts, the required levels were not achieved. Further reductions in  $\text{NO}_x$  for the JT8D-17 and the TFE 731-2 engine advanced concepts should be attainable with further development but it is unlikely that further appreciable reductions can be achieved with the vorbix 58-5C configuration without adversely affecting performance. Therefore, the advanced technology concepts that are being developed for the JT8D-17 engine will not be capable of reducing  $\text{NO}_x$  to the EPAP of 3.0 required by the EPA standards. The TFE 731-2 engine advanced concepts have not been completely evaluated and a final judgment regarding their capability to reduce  $\text{NO}_x$  cannot be made at this time.

The combustor performance (combustion efficiency, pressure drop, and exit temperature pattern factor) that was obtained for all of the advanced concepts was acceptable with the exception of pattern factor which will require further development for the JT8D-17 and TFE 731-2 configurations. Other factors such as altitude relight and fuel staging (where applicable) appear to be within developable limits although considerably more data are needed from both combustor rig tests (Phase II) and actual engine demonstration tests (Phase III), before quantitative conclusions can be reached. Verification of the combustor rig emission data in actual engines is also needed but the levels listed in Tables VIII, X, and XII are judged to be representative of expected engine values. Possible variations may occur due to engine component airflow variations and fuel staging trade-offs (on the staged designs) that may be necessary to achieve acceptable engine accelerations.

## ASSESSMENT OF RESULTS

In assessing the impact of the advanced technology combustors on both current and future aircraft gas turbine engines, prime emphasis will be placed on the ability to control the emission levels of CO, THC, NO<sub>x</sub>, and smoke and on the ability to maintain acceptable performance characteristics. The assessment will also emphasize the application to newly manufactured engines rather than retrofit. Retrofit considerations were not included in the contract programs.

The results obtained to date from the ECCP and PRTP provide comprehensive definitive data regarding emissions and performance. Operational factors, such as altitude relight, durability, coking, staging characteristics, etc., were not evaluated to the same detail and, therefore, the available information regarding these factors is less complete and is in some cases more qualitative than quantitative. The prime objective of NASA was to evolve advanced technology combustor concepts for reducing emissions while considering, but not attempting to provide for, the normal development activities that must be undertaken to satisfy operational characteristics. The Phase III engine demonstration tests will provide more information regarding these factors. Because of the above considerations, only qualitative judgments will be offered with regard to assessing the impact of the advanced concepts on the operational characteristics of the engines. Also, the assessment will address other such factors as the impact of engine variability and development on emission levels, combustor complexity, and development time only in a qualitative sense.

## Emissions

From the results of all the tests conducted to date (as described in the STATUS AND RESULTS section), a selection was made of the most promising advanced technology combustor concept for each engine considered in the ECCP and PRTP. A summary of the emission levels achieved with these concepts as compared to the respective engine baseline combustors and the 1979 EPA standards is presented in Table XIV. All values shown are in terms of EPAP levels corrected to actual engine operating conditions.

Analysis of results. - All of the selected advanced concepts produced emission levels of THC and smoke that were below the levels needed to meet the EPA standards. The CF6-50 double annular concept and the 501-D22A reverse flow concept reduced the CO emissions to values less than EPA standards. The 501-D22A reverse flow concept was the only one that was capable of achieving NO<sub>x</sub> emission levels below the EPA standards. The prime reason for the success of the 501-D22A concept in achieving the NO<sub>x</sub> emission level requirements is due to the low initial level for the baseline combustor as compared to the EPA standards. The JT9D-7 vorbix concept, the JT8D-17 vorbix concept, and the TFE 731-2 piloted-airblast concept did not achieve CO emission levels low enough to meet the EPA standards. Further reductions in CO

levels should be achievable with the vorbix concepts through continued development, but whether the standard levels can be achieved is uncertain at this time. The piloted-airblast concept should be capable of achieving the EPA standards for CO with further development. As shown in Table XIV, the  $\text{NO}_x$  emission levels were not low enough to satisfy the EPA standards for four out of five of the advanced concepts. The TFE 731-2 piloted-airblast concept data is too preliminary to make a final judgment as to the achievable levels. Some reduction is certainly possible but the magnitude of this reduction has not been quantified.

The principal reason for the "short fall" in  $\text{NO}_x$  emission level reduction, compared to the EPA standards, can be attributed to the inability to make maximum use of the lean burning approach to control  $\text{NO}_x$  (described in the EMISSION REDUCTION TECHNOLOGY section) in the advanced concepts. In all cases, lean burning and quick quenching techniques were employed in the main stages but the effectiveness of lean burning is significantly reduced unless the fuel is prevaporized and premixed with the combustor inlet air prior to the combustion process. The technology needed to design and evolve effective and practical prevaporized/premixed concepts is still several years in the future. Therefore, the reductions in  $\text{NO}_x$  emission levels presented in Table XIV are probably the "best" attainable with the level of advanced technology developed for the CF6-50, JT9D-7 and JT8D-7 engines. The term "best" is used here to describe the level of the achievable reductions bearing in mind that variations about this level will likely occur with the application of these advanced technology combustor concepts to operational aircraft engines. Some of these potential variations will be discussed subsequently.

Engine cycle considerations. - In comparing the minimum levels of  $\text{NO}_x$  emissions achieved by the various advanced concepts, variations are certainly apparent. One factor that is paramount in the production of  $\text{NO}_x$  is combustion flame temperature (see figure 5). In a diffusion flame process (fuel droplet burning), the flame temperature is principally controlled by the inlet temperature ( $T_3$ ) and pressure ( $P_3$ ) of the air entering the combustion zone. A comparison of these two parameters for the five engines considered in the ECCP and P RTP is given in Table XV for the two extreme operating conditions, idle and sea level take-off (SLTO). The values of  $P_3$  and  $T_3$  are, of course, directly the result of engine cycle pressure ratio. If we consider only the T2 class engines (CF6-50 and JT9D-7), an appreciable difference in inlet pressure and temperature is noted. The impact that these differences can have on  $\text{NO}_x$  emissions is illustrated in figure 14 where  $\text{NO}_x$  E.I. is plotted as a function of combustor inlet temperature. The range of inlet temperature shown on figure 14 encompasses all of the engines considered in the ECCP and P RTP. The upper curve, designated as that which applies to current conventional combustor emission characteristics, is from reference 22.

Actual values for all of the ECCP and P RTP engine baseline combustors are indicated by the open symbols on this figure and although they do not precisely fit the conventional combustor curve they do follow the same trend. Also shown for reference is a curve obtained from test results of the swirl-can-modular combustor tested at the Lewis Research Center and the values obtained from the "best"

advanced concepts tested in the ECCP and P RTP (solid symbols). The CF6-50, JT9D-7 and JT8D-17 engine advanced concept results agree quite closely with the swirl can combustor results in terms of both level of reduction and the trend of  $\text{NO}_x$  production with inlet temperature. The 501-D22A engine reverse flow concept results tend to agree with the conventional combustor  $\text{NO}_x$  values which is to be expected since the reverse flow concept was designed to primarily reduce CO and THC emissions at low power. These results clearly illustrate that the advanced concepts tested in the ECCP and P RTP to date produced varying levels of  $\text{NO}_x$  emissions which were dependent upon the combustor inlet temperature (cycle pressure ratio) of the intended engine application and the level of technology employed. From the standpoint of establishing an achievable goal value for  $\text{NO}_x$  emissions, it is important that the fundamental relationship between  $\text{NO}_x$  emissions and combustor inlet temperature be taken into account regardless of combustor technology level and engine cycle, size, or thrust level.

The use of engine specific fuel consumption (SFC) as a modifying parameter to account for improvements in engine cycle thermal efficiency that are realized by increasing pressure ratio, does provide for some variability of emission levels in the EPAP calculation:

$$\text{EPAP} \approx \sqrt{\text{E.I.} \times \text{SFC}} \quad (2)$$

Reductions in SFC permit a higher E.I. for a given value of EPAP. However,  $\text{NO}_x$  emission levels increase with combustor inlet temperature in accordance with the relationship:

$$\frac{\text{NO}_x}{(\text{NO}_x)_{\text{ref}}} = e^{1.14 \left[ \frac{T_3}{288 \text{ K}} - \frac{(T_3)_{\text{ref}}}{288 \text{ K}} \right]} \times \left[ \frac{P_3}{(P_3)_{\text{ref}}} \right]^{\frac{1}{2}} \quad (3)$$

whereas the SFC is not decreased by the same proportion as cycle pressure ratio is increased. This effect is illustrated in figure 15 where relative values of SFC (at fixed engine bypass ratios) and  $\text{NO}_x$  are plotted as a function of engine cycle pressure ratio. The reference SFC values represent a series of optimized engine cycle calculations (see reference 23) and not variations that would result from changes to a specific engine. Varying engine cycle pressure ratio to change engine SFC would be accompanied by corresponding variations in  $\text{NO}_x$  emissions levels for a fixed level of combustor technology. As an example, increasing engine cycle pressure ratio from 20 to 30, at a fixed bypass ratio of 7, would result in a

computed decrease in SFC of approximately 8 percent but the resultant computed increase in  $\text{NO}_x$  emission index (equation 3) would be approximately 45 percent. Thus, the modifying effect of decreased SFC in the EPAP calculation would not compensate for the expected increase in  $\text{NO}_x$  emission even though the combustor technology would be comparable. This effect is extremely important when judging the ability of two engines of varying pressure ratio, to achieve a fixed  $\text{NO}_x$  emission control level even though their SFC may be different. In the consideration of future engine cycles, simultaneously increasing pressure ratio and bypass ratio (20 to 30 and 7 to 10) could provide a further decrease in SFC (approximately 18 percent) for the same increase (approximately 45 percent) in  $\text{NO}_x$  emission index. These considerations are not meant to provide quantitative trade-offs for the evaluation of parameters to judge, compare, or regulate engine emissions. They do, however, point out some of the important factors that must be considered when evaluating the capability of aircraft gas turbine engine combustors (conventional or advanced technology) to comply with established emission level goals or regulations.

One potential future benefit of the advanced technology combustor concepts tested in the ECCP and PRTP is illustrated in figure 16 where  $\text{NO}_x$  E.I.'s calculated from equation (3), using the CF6-50 baseline combustor and double annular concept emissions as reference points, are plotted as a function of engine cycle pressure ratio. Even though the percentage increase in  $\text{NO}_x$  with pressure ratio is maintained constant, the actual increase in  $\text{NO}_x$  E.I. is significantly lower for the double annular as compared to the conventional combustor. For example, increasing pressure ratio from 20 to 30 increases  $\text{NO}_x$  E.I. by 17 for the baseline combustor versus an increase of only 7 for the double annular. This characteristic is an important consideration for assessing the impact of advanced technology on future aircraft engine emissions.

Emission assessment summary. - The reductions in emission levels achieved by the selected advanced technology combustors, as compared to the conventional baseline engine combustors, are significant and from an emission reduction aspect certainly warrant continued development. The actual level of  $\text{NO}_x$  emissions achieved with the staged double annular and vortex concepts, as listed in Table XIV, are judged to be representative of the "best" values that can be achieved with the level of technology currently being developed. Further decreases will require the implementation of techniques that are still in the fundamental study phase of development. Implementation of advanced technology combustors in aircraft engines will result in cruise  $\text{NO}_x$  reductions as well as reductions for the LTO cycle and, as such, represent an attractive approach for improving air quality in both the low and high altitude aircraft operating regimes.

Additional  $\text{NO}_x$  emissions reductions are possible by using water injection as discussed in the EMISSION REDUCTION TECHNOLOGY section and as illustrated in figure 6. The effect of water injection on  $\text{NO}_x$  was evaluated on the modified baseline combustor for the TFE 731-2 engine and the effectiveness was similar to that shown in figure 6. The problems in implementing water injection in aircraft and in ground handling have been described in reference 24 and will not be discussed



in this report.

The emission levels that are to be used to establish goals and/or standards that must be achieved (particularly for  $\text{NO}_x$ ), should be carefully chosen and include all of the prominent fundamental factors, such as combustor inlet temperature and pressure, as well as other factors that pertain to engine efficiency, such as SFC.

Based on the emission reduction results obtained to date in the ECCP, PRTP, and the NASA in-house studies, a qualitative assessment of the ability of the various control techniques to reduce engine emissions was made and is summarized in Table XVI. The relative degree of difficulty estimated to accomplish a successful engine application and the estimated time required to achieve such an application in new production engines are also shown. Most of the minor to moderate modifications would be variations of existing baseline combustor concepts, such as the 501-D22A engine reverse flow concept shown in figure 12B. As such, they are judged to have a low or low to moderate "development risk." The term "development risk" is defined as the estimated degree of difficulty required to convert a demonstrated experimental technique into a production combustor for a newly manufactured engine. The estimated implementation times shown refer to the period of time required to attain in-service status after a "proof-of-concept" test, similar to the planned engine demonstration tests, has been successfully completed. The estimated implementation times for the staged double annular and vorbix concepts is based on allowing 12 to 18 months for the design, fabrication and procurement of production type hardware, 18 to 24 months for combustor component and engine development testing (both ground and flight), 6 months for qualification tests and FAA certification, and a 12 month service evaluation (if needed). The principal factors contributing to the uncertainty (3 to 5 years) in determining an accurate implementation time is the unknown impact of the increased complexity on the design and fabrication of hardware, and on achieving successful combustor, fuel system, and fuel control development during the component and engine tests and whether or not a service evaluation period is required. The minor to moderate combustor modifications are estimated to require considerably shorter time periods for design and fabrication (6 months) and testing (12 to 18 months) because the complexity factor is reduced and much of the present engine fuel system and fuel control would be unaffected. Also a shorter service evaluation time would be anticipated if one is required prior to establishing emission level requirements.

### Overall Performance

Combustion parameters. - The overall performance results for the selected "best" advanced technology combustor concepts are presented in Table XVII. Combustion efficiencies at all the LTO cycle operating points are in excess of 99 percent. At approach and high power conditions (climbout and takeoff), combustion efficiencies were virtually 100 percent which is comparable to baseline engine combustor

performance. The idle efficiencies represent substantial increases from the baseline combustors due to the reductions in THC and CO obtained. Pressure drop was maintained nearly equal to the baseline combustor values and is not listed since it is compatible to engine requirements.

Exit temperature pattern factors of the advanced concepts varied from approximately 0.6 of the baseline combustor value for the 501-D22A reverse flow concept to a factor of nearly 2 higher for the TFE 731-2 piloted-airblast concept. In general, most of the advanced concepts had higher pattern factors than their comparable baseline combustors but it should be borne in mind that these concepts are still in an experimental stage of development. Reductions of the magnitude required to achieve comparability with the baseline values is not uncommon during combustor development and, therefore, these higher pattern factors are not judged to be a critical impediment to successful engine application.

Altitude relight. - The altitude relight characteristics of the advanced concepts have been and continue to be evaluated during the Phase I and II efforts of both the ECCP and the PRTP. In general, most of them have not yet achieved all of the altitude relight requirements of their respective engines and some have not yet entered into the altitude relight evaluation phase of testing. Altitude relight results obtained to date in the ECCP (reference 18) are encouraging for this stage of combustor development and, as in the pattern factor situation, the obtainment of acceptable altitude relight should be attainable during normal combustor development.

### Engine Considerations

Complexity factors. - One important factor that must be considered in assessing the applicability of converting the advanced concepts into production type engine combustors is the impact of the increased complexity of some of these concepts compared to the baseline combustors currently in use. No significant problems would be expected in applying the reverse flow concept to the 501-D22A engine since minimal or no changes in the engine fuel system and fuel control functions should be necessary. Applying the piloted-airblast concept to the TFE 731-2 engine would require some changes to the engine/combustor structure but would not be expected to significantly effect the engine fuel system or control. This concept, although necessitating more changes to the engine than the reverse flow, is therefore not judged to be a major increase in complexity. The staged double annular and vorbix concepts will certainly increase the complexity of both the engine fuel system and the required control functions. The number of fuel injectors needed to adapt the staged double annular concept to the CF6-50 engine would be increased by more than a factor of 2 above the number currently used in the baseline combustor. The same order of increase is also required to adapt the vorbix concepts to the JT9D-7 and JT8D-17 engines. In addition, the staged concepts would require an additional fuel manifold and the fuel

flow to the two manifolds must be controlled independently and accurately. Studies conducted by both GE and P&WA during Phase II of the ECCP have shown that this increase in complexity is of concern and will require further development. However, at this time it does not appear to be an insurmountable problem to the successful application of the staged concepts to the CF6-50, JT9D-7, or JT8D-17 engines. Hydromechanical controls have been designed and used in military engines to handle the type of dual flow functions required. The probability of electronic digital fuel control systems entering service in the future would make this required dual control mode much more positive and easier to manage.

Operational factors. - Many operational factors that must be met to insure successful engine application have not yet been completely evaluated. Meeting engine starting requirements, acceleration and deceleration requirements, and finally verifying emission levels with engine imposed variations in flow, temperature, and pressure profiles (the "real world" compared to the controlled environment of the combustor test rigs) have not yet been evaluated. These factors will be explored in the engine demonstrations to be conducted during 1976 and 1977 and until they are quantitatively evaluated, it is not possible to determine if trade-offs between engine requirements and emission levels are going to be necessary. Although some variations in emission levels are anticipated in the actual engines, the levels of emission reduction obtained in the rig tests are felt to be representative because most of the engine contractors have obtained satisfactory correlations between rig and engine test values for their current baseline combustors. Successful combustor light-offs and reasonably smooth transitions observed during staging (for the double annular and vortex concepts) in the combustor rig tests would also seem to indicate that significant trade-offs of emissions versus operational performance are not likely to be required. The inability to maintain accurate and repeatable control of the staging point during acceleration and deceleration is likely to be the most difficult problem.

In-service factors. - Many in-service factors could impact the final achievable emission levels of the advanced concepts when they are implemented in production type engines. These in-service factors have not been considered because the ECCP and P RTP are aimed at evaluating and demonstrating the emission reduction potential of various control techniques rather than service suitability. Nevertheless, in-service factors must be considered when determining final achievable levels for engine emission control. Some of the more prominent factors that must be considered are: engine to engine variations which result from differences in component matching; variations that could result due to development problems such as the trade-offs that were previously described; deterioration of component performance with time; and variations that could result from operational differences such as variations in compressor bleed at idle, see Table VI. Although NASA does not have data regarding these factors, engine manufacturers do have representative values that have been obtained from conventional engine combustors. As an example, DDA suggested that the emission level goals for the 501-D22A engine advanced technology combustor concepts be set 25 percent below the EPA

standards. This was estimated to be a "comfortable" cushion for developmental trade-offs and compromises. The actual impact of these factors on achievable in-service engine emission levels cannot be quantitatively defined for the advanced technology combustors at this time. Until data are obtained, it may be advisable to provide an emission level margin in the control values that is based on available conventional engine/combustor emission variations.

#### CONCLUDING REMARKS

Although the NASA Experimental Clean Combustor Program (ECCP) and Pollution Reduction Technology Program (P RTP) are in various stages of program completion, a considerable amount of emissions, performance, and operational data have been accumulated. These data together with preliminary considerations of engine application requirements, provide a reasonable indication of the potential of advanced technology combustors for reducing current jet aircraft engine emissions while maintaining satisfactory engine performance and operation. In addition, fundamental and applied research studies being conducted at the NASA Lewis Research Center, other government agencies, and private industry are providing data regarding the emission reduction capability of future generation aircraft gas turbine engines.

The results of the ECCP and P RTP indicate that significant reductions in the levels of all pollutant emissions (CO, THC, NO<sub>x</sub> and smoke) can be achieved by employing advanced technology combustor concepts in selected engines representative of four of the six aircraft gas turbine engine classes specified in the EPA standards. Simultaneous reduction of all the emissions, over the entire range of engine operation, required the use of staged combustion techniques. The added complexity involved in the staged concepts (increased fuel injectors, multiple fuel manifolds, multiple burning zones, and added fuel control functions) will require continued development beyond the scope of the current programs. The development risk involved in converting the staged concepts to production type hardware is not judged to be prohibitive based on the results obtained to date. However, "proof-of-concept" type tests in full-scale engines is needed to quantify the success of these concepts in terms of the absolute levels of emissions that are achievable and to demonstrate the capability to successfully satisfy all of the engine operational requirements. Selective reductions in certain emission levels, e.g. CO and THC, can be achieved by employing relatively minor to moderate modifications to current engine baseline combustors at a much lower development risk and in a much shorter estimated time period. The range of emission level reductions obtained in the ECCP and P RTP, as compared to the complexity and the estimated development risk and time factors, provides a large data bank for evaluating the trade-offs necessary for the final establishment of emission level controls. Because of the inherent total emission control capability of the staged combustor concepts, the continued development of these concepts for application to future newly manufactured engines seems highly desirable.

In the evaluation of emissions levels that can be achieved by employing advanced technology, considerable care must be taken to account for all of the factors which influence the rate of formation of the pollutants during the combustion process. Paramount among these factors are the combustor inlet pressure and temperature which are direct functions of the engine cycle pressure ratio. Since most modern day engines employ high pressure ratio, particularly the high bypass ratio engines, the emission index (E.I.) levels for  $\text{NO}_x$  have been steadily increasing for conventional type combustors. Even though the staged combustor concepts investigated in the ECCP and PRTP employ lean combustion techniques which decrease the level of  $\text{NO}_x$  formed at a given operating point, the characteristic trait of increasing  $\text{NO}_x$  E.I. with increasing pressure ratio still exists. Thus, when trying to establish a technologically equitable value for controlling  $\text{NO}_x$  emission levels, a fixed value such as a constant EPAP could be either too strict for a high pressure ratio engine or too lenient for a low pressure ratio engine depending on how the base value was selected. The use of variations in specific fuel consumption (SFC) as a modifier to compensate for variations in E.I. at a fixed EPAP does not fully compensate for the magnitude of the  $\text{NO}_x$  increases that would result from variations in cycle pressure ratio. As an example, increasing the cycle pressure ratio from 20 to 30 at a fixed bypass ratio of 7 would reduce the relative SFC by approximately 8 percent as compared to an increase in the relative  $\text{NO}_x$  emission index of approximately 45 percent. In consideration of these factors, a renewed effort should be undertaken to develop a technologically equitable approach for establishing emission level controls for both newly manufactured and future generation aircraft gas turbine engines. The next generation of aircraft gas turbine engines may employ very high pressure ratios (40 to 50) to achieve low energy consumption. This will further aggravate the impact of combustor inlet conditions on the ability of advanced technology to control  $\text{NO}_x$  emission levels to some fixed level. Other factors that are related to engine operational considerations, such as engine to engine variations, developmental variations, and the impact of in-service deterioration, must also be considered when judging the capability of the advanced combustor concepts to reduce emissions levels for operational in-service engines.

Results of fundamental combustion studies indicate that a new generation of jet aircraft engine combustor technology may be possible that would provide emission levels far below those currently possible with the advanced technology concepts developed in the ECCP and PRTP. Considerable fundamental knowledge is still needed, however, before the techniques being studied can be translated into useful combustors. This translation is not likely to occur until the late 1980's.

In general, NASA's assessment of the emission reduction technology results obtained to date, indicates that the adaption of a variety of emission control techniques to advanced technology combustor concepts has been successful and that given a reasonable length of time (period will depend on the complexity of the chosen technique) these concepts can be developed into acceptable combustors for a variety of aircraft engine types currently in service. Staged

combustor concepts would be primarily for newly manufactured engines of both current and future types and not for retrofit into existing in-service engines. No prohibitive problems were encountered in effectively converting emission control techniques into advanced technology combustor concepts for five different aircraft gas turbine engines of varying types and sizes.

## REFERENCES

1. Control of Air Pollution For Aircraft Engines - Emission Standards and Test Procedures for Aircraft. Federal Register, Vol. 38, July 17, 1973, pp. 19088-19103.
2. Ingebo, Robert D.; and Norgren, Carl T.: Effect of Primary - Zone Water Injection on Pollutants from a Combustor Burning Liquid ASTM A-1 and Vaporized Propane Fuels. NASA TN D-7293, 1973.
3. Jones, Robert E.; and Grobman, Jack S.: Design and Evaluation of Combustors for Reducing Aircraft Engine Pollution. NASA TM X-68192, 1973.
4. Niedzwiecki, Richard W.; and Jones, Robert E.: Parametric Test Results of a Swirl Can Combustor. NASA TM X-68247, 1973.
5. Grobman, Jack S.; and Papathakos, Leonidas C.: Smoke Evaluation of Modified J-57 Combustor. NASA TM X-2236, 1971.
6. Glassman, Irving: Combustion Science and Technology. Princeton University, 1970.
7. Papathakos, Leonidas C.; and Jones, Robert E.: Use of Air-Assested Fuel Nozzle to Reduce Idle Emissions of a JT8D Engine Combustor. NASA TM X-2946, 1973.
8. Ingebo, Robert D.; and Norgren, Carl T.: High-Pressure Combustor Exhaust Emissions with Improved Air-Atomizing and Conventional Pressure Atomizing Fuel Nozzles. NASA TN D-7154, 1973.
9. Clements, T. R.: Effects of Fuel Zoning and Fuel Nozzle Design on Pollution Emissions at Ground Idle Conditions for a Double-Annular Ram-Induction Combustor. NASA CR-121094, 1973.
10. Anderson, David N.: Effect of Hydrogen Injection on Stability and Emissions of an Experimental Premixed Prevaporized Propane Burner. NASA TM X-3301, 1975.
11. Roffe, G.; and Ferri, A.: Prevaporization and Premixing to

Obtain Low Oxides of Nitrogen in Gas Turbine Combustors. NASA CR-2495, 1975.

12. Roberts, P. B; While, D. J.; and Shekleton, J. R.: Advanced Low NO<sub>x</sub> Combustors for Supersonic High-Altitude Aircraft Gas Turbines. NASA CR-134889, 1975.
13. Mularz, Edward J.; Wear, Jerrold D.; and Verbulecz, Peter W.: Exhaust Pollutant Emissions from Swirl-Can Combustor Module Arrays at Parametric Test Conditions. NASA TM X-3237, 1975.
14. Biaglow, James A.; and Trout, Arthur M.: Performance and Pollution Measurements of Two-Row Swirl-Can Combustor Having 72 Modules. NASA TM X-3170, 1975.
15. Biaglow, James A.; and Trout, Arthur M.: Idle Efficiency and Pollution Results for Two-Row Swirl-Can Combustor Having 72 Modules. NASA TM X-3208, 1975.
16. Schultz, Donald F.: Exhaust Emissions of a Double Annular Combustor - Parametric Study. NASA TM X-3163, 1975.
17. Niedzwiecki, Richard W.; and Jones, Robert E.: The Experimental Clean Combustor Program - Description and Status. NASA TM X-71547, 1974.
18. Niedzwiecki, Richard W.: The Experimental Clean Combustor Program - Description and Status to November 1975. NASA TM X-71849, 1975.
19. Roberts, R.; Peduzzi, A.; and Vitti, G. E.: Experimental Clean Combustor Program, Phase I Final Report. NASA CR-134736, 1975.
20. Grobecker, A. J.; Coroniti, S. C.; and Cannon, R. H., Jr.: The Effects of Stratospheric Pollution by Aircraft, Report of Findings. DOT-TST-75-50, 1974.
21. Bahr, D. W.; and Gleason, C. C.: Experimental Clean Combustor Program, Phase I Final Report. NASA CR-134737, 1975.
22. Rudey, Richard A.; and Kempke, Erwin E., Jr.: Technology for Reducing Aircraft Engine Pollution. NASA TM X-71670, 1975.



23. Rudey, Richard A.: The Long Term Energy Problem and Aeronautics, NASA/University Conference on Aeronautics. NASA SP-372, 1974.
24. Grobman, Jack S., et al.: Combustion and Emissions Technology, Aeronautical Propulsion Conference. NASA SP-381, 1975.

TABLE I. - IDLE POLLUTION CONSIDERATIONS  
 PRINCIPAL IDLE POLLUTANTS: CO & THC  
 PRINCIPAL CAUSES: LOW VALUES OF FUEL NOZZLE  
 PRESSURE DROP, FUEL/AIR RATIO, COMBUSTOR  
 INLET TEMP & PRESSURE

POLLUTION MECHANISM	CORRECTION
POOR ATOMIZATION & DISTRIBUTION	IMPROVE ATOMIZATION & DISTRIBUTION
POOR COMBUSTION STABILITY	INCREASE EQUIVALENCE RATIO TO 1
QUENCHING	INCREASE RESIDENCE TIME REDUCE VELOCITY DELAY MIXING

CS-73148

TABLE II. - FULL POWER POLLUTION CONSIDERATIONS

PRINCIPAL POLLUTANT: NO<sub>x</sub>  
 PRINCIPAL CAUSES: HIGH VALUES OF COMBUSTOR INLET TEMP,  
 PRESSURE, & FUEL/AIR RATIO

POLLUTION MECHANISM	CORRECTION
HIGH FLAME TEMP	LOWER FLAME TEMP BY ADDING DILUENTS (WATER) BURNING LEANER MIXTURES PREMIXING FUEL & AIR PREVAPORIZING FUEL
EXCESSIVE RESIDENCE TIME	REDUCE RESIDENCE TIME BY INCREASING VELOCITY RAPID QUENCHING

CS-73149

TABLE III. - OVERALL POLLUTION CONSIDERATIONS

POLLUTANT REDUCTION APPROACH	
CO & THC	NO <sub>x</sub>
BURN STOICHIOMETRIC MIXTURE	BURN LEAN MIXTURE
MAXIMIZE RESIDENCE TIME	MINIMIZE RESIDENCE TIME
IMPROVE FUEL ATOMIZATION & DISTRIBUTION	

CS-73138

ORIGINAL PAGE IS  
 OF POOR QUALITY

PRECEDING PAGE BLANK NOT FILMED

TABLE IV. - SUMMARY OF EMISSION LEVELS ACHIEVED WITH "SELECTED" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR THE CF6-50 ENGINE. ECCP PHASE II. VALUES AT DISCRETE OPERATING CONDITIONS ARE IN EMISSION INDEX (E.I.)

CONFIGURATION	OPERATING CONDITION	EMISSIONS			
		CO	THC	NO <sub>x</sub>	SMOKE
CF6-50 ENGINE BASELINE COMBUSTOR	IDLE	73	30	2.5	13
	APPROACH	4.3	-----	10.0	
	CLIMBOUT	-----	-----	29.5	
	SLTO	-----	-----	35.5	
	EPAP	10.8	4.3	7.7	
	CRUISE				
DOUBLE ANNULAR CONCEPT CONFIG: D/A-13	IDLE	19.3	2.2	3.0	
	APPROACH <sup>oo</sup>	3.1	-----	12.8	
	CLIMBOUT	-----	-----	13.3	
	SLTO	-----	-----	16.9	
	EPAP	3.0	.3	4.25	
	CRUISE	8.8	.17	8.0	
RADIAL/AXIAL CONCEPT CONFIG: R/A-2	IDLE	53.8	6.1	3.1	
	APPROACH <sup>oo</sup>	1.3	.2	9.2	
	CLIMBOUT	10.9	.2	14.2	
	SLTO	8.5	.1	16.1	
	EPAP	9.56	.88	4.30	
	CRUISE				
1979 EPA STANDARDS	EPAP	4.3	0.8	3.0	<5

<sup>a</sup>ALL VALUES COMPUTED AT ACTUAL ENGINE OPERATING CONDITIONS (STANDARD DAY).

<sup>oo</sup>PILOT STAGE ONLY FUELED AT APPROACH.

TABLE V. - SUMMARY OF PERFORMANCE RESULTS ACHIEVED WITH "SELECTED" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR THE CF6-50 ENGINE. ECCP, PHASE II. PRESSURE DROP,  $\Delta p/p$ , SAME AS BASELINE FOR ALL CONCEPTS

CONFIGURATION	OPERATING CONDITION	COMBUSTION EFF, %	EXIT TEMP PATTERN FACTOR
			$\frac{T_{MAX} - T_{AVE}}{T_{AVE} - T_{IN}}$
CF6-50 ENGINE BASELINE COMBUSTOR	IDLE	95.3	
	APPROACH	-----	
	CLIMBOUT	-----	
	SLTO	100	
DOUBLE ANNULAR CONCEPT CONFIG: D/A-13	IDLE	99.3	1.5 x BASELINE 1.5 x BASELINE
	APPROACH	99.9	
	CLIMBOUT	100	
	SLTO	100	
RADIAL/AXIAL CONCEPT CONFIG: R/A-2	IDLE	98.1	≈ BASELINE ≈ BASELINE
	APPROACH	100	
	CLIMBOUT	99.8	
	SLTO	99.8	

FINAL PAGE IS  
FOR QUALITY

TABLE VI. - SUMMARY OF EMISSION LEVELS ACHIEVED WITH "SELECTED" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR THE JT9D-7 ENGINE. ECCP, PHASE II. EMISSION VALUES AT DISCRETE OPERATING CONDITIONS ARE IN EMISSION INDEX (E. I.)

CONFIGURATION	OPERATING CONDITION	EMISSIONS			
		CO	THC	NO <sub>x</sub>	SMOKE
JT9D-7 ENGINE BASELINE COMBUSTOR	IDLE #1 <sup>+</sup>	-----	-----	-----	10
	IDLE #2 <sup>+</sup>	77	29.8	3.3	
	APPROACH	9.6	1.0	8.4	
	CLIMB	-----	-----	22.9	
	SLTO	-----	-----	31.5	
	EPAP #2 CRUISE	14.29	5.34	4.90	
VORBIX CONCEPT CONFIG: S-20	IDLE #1 <sup>+</sup>	46.3	8.0	3.0	
	IDLE #2 <sup>+</sup>	26.4	4.7	3.9	
	APPROACH	9.7	.2	8.6	
	CLIMB	2.1	-----	14.9	
	SLTO	16.9	.1	14.6	
	EPAP #1	9.56	1.12	3.30	
	EPAP #2	6.25	.64	3.48	
	CRUISE	26.7	.09	7.1	
HYBRID CONCEPT CONFIG: H-6	IDLE #1 <sup>+</sup>	9.6	4.2	3.6	
	IDLE #2 <sup>+</sup>	3.5	2.8	2.8	
	APPROACH <sup>***</sup>	-----	.2	15.2	
	CLIMB	21.6	1.5	11.6	
	SLTO	8.9	1.1	16.4	
	EPAP #1	4.32	.94	3.56	
	EPAP #2	3.29	.71	3.45	
	CRUISE	34.6	6.02	7.5	
EPA 1979 STANDARDS	EPAP	4.3	0.8	3.0	<25

<sup>+</sup> BLEED, REF. 18.

<sup>+</sup> UNBLEED, REF. 18.

<sup>\*</sup> ALL VALUES COMPUTED AT ACTUAL ENGINE OPERATING CONDITIONS (STANDARD DAY).

<sup>\*\*</sup> PILOT STAGE ONLY FUELED AT APPROACH.

TABLE VII. - SUMMARY OF PERFORMANCE RESULTS ACHIEVED WITH "SELECTED" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR THE JT9D-7 ENGINE. ECCP, PHASE II. PRESSURE DROP,  $\Delta p/p$ , SAME AS BASELINE FOR ALL CONCEPTS

CONFIGURATION	OPERATING CONDITION	COMBUSTION EFF, %	EXIT TEMP PATTERN FACTOR $\frac{T_{MAX} - T_{AVE}}{T_{AVE} - T_{IN}}$
JT9D-7 ENGINE BASELINE COMBUSTOR	<sup>*</sup> IDLE	95.2	
	APPROACH	99.7	
	CLIMBOUT	100	
	SLTO	100	
VORBIX CONCEPT CONFIG: S-20	<sup>*</sup> IDLE	99.0	1.5 x BASELINE 1.5 x BASELINE
	APPROACH	99.8	
	CLIMBOUT	100	
	SLTO	99.6	
HYBRID CONCEPT CONFIG: H-6	<sup>*</sup> IDLE	99.4	> BASELINE > BASELINE
	APPROACH	99.6	
	CLIMBOUT	100	
	SLTO	99.7	

<sup>\*</sup> IDLE #2 - UNBLEED, REF. 18.

TABLE VIII. - SUMMARY OF EMISSION LEVELS ACHIEVED WITH "SELECTED" ADVANCED  
TECHNOLOGY COMBUSTOR CONCEPTS FOR THE JT8D-17 ENGINE. PRTP, PHASE I.

VALUES AT DISCRETE OPERATING POINTS ARE IN EMISSION INDEX (E.I.)

CONFIGURATION	OPERATING CONDITION	EMISSIONS			
		CO	THC	NO <sub>x</sub>	SMOKE
JT8D-17 ENGINE BASELINE COMBUSTOR	IDLE	44.5	12.8	3.7	28
	APPROACH	7.5	.7	8.5	
	CLIMBOUT	----	----	20	
	SLTO	----	----	24	
	EPAP	16.1	4.4	8.2	
	CRUISE	3	----	11	
MODIFIED BASELINE COMBUSTOR CONFIG: "LEAN FRONT END"	IDLE	19.1	3.8	3.3	11
	APPROACH	2.4	1.5	6.6	
	CLIMBOUT	----	----	17.8	
	SLTO	----	----	25	
	EPAP	6.8	1.5	7.4	
	CRUISE	----	----	----	
VORBIX CONCEPT CONFIG: 58-5C	IDLE	18.7	----	2.6	26
	APPROACH	4.9	----	5.7	
	CLIMBOUT	7.8	----	9.1	
	SLTO	6.8	----	11.5	
	EPAP	9.0	.2	4.3	
	CRUISE	4	----	7.6	
EPA 1979 STANDARDS	EPAP	4.3	0.8	3.0	<25

\*ALL VALUES COMPUTED AT ACTUAL ENGINE OPERATING CONDITIONS (STANDARD DAY).

TABLE IX. - SUMMARY OF PERFORMANCE RESULTS ACHIEVED BY "SELECTED" ADVANCED  
TECHNOLOGY COMBUSTOR CONCEPTS FOR THE JT8D-17 ENGINE. PRTP, PHASE I.

PRESSURE DROP,  $\Delta p/p$ , SAME AS BASELINE FOR ALL CONCEPTS

CONFIGURATION	OPERATING CONDITION	COMBUSTION EFF. %	EXIT TEMP PATTERN FACTOR, $\frac{T_{MAX} - T_{AVE}}{T_{AVE} - T_{IN}}$
JT8D-17 ENGINE BASELINE COMBUSTOR	IDLE	97.7	
	APPROACH	99.8	
	CLIMBOUT	100	
	SLTO	100	
MODIFIED BASELINE COMBUSTOR CONFIG: "LEAN FRONT END"	IDLE	99.2	< BASELINE < BASELINE
	APPROACH	99.8	
	CLIMBOUT	100	
	SLTO	100	
VORBIX CONCEPT CONFIG: 58-53	IDLE	99.5	1.7 x BASELINE 1.7 x BASELINE
	APPROACH	99.9	
	CLIMBOUT	99.8	
	SLTO	99.8	

TABLE X. - SUMMARY OF EMISSION LEVELS ACHIEVED WITH "SELECTED" ADVANCED TECHNOLOGY  
COMBUSTOR CONCEPTS FOR THE TFE731-2 ENGINE. PRTP, PHASE I. VALUES AT DISCRETE  
OPERATING POINTS ARE IN EMISSION INDEX (E.I.)

CONFIGURATION	OPERATING CONDITION	EMISSIONS			
		CO	THC	NO <sub>x</sub>	SMOKE
TFE 731-2 ENGINE BASELINE COMBUSTOR	IDLE	57.9	17.3		
	APPROACH				
	CLIMBOUT				
	SLTO			18.8	16
	EPAP	17.5	5.3	5.3	
MODIFIED BASELINE COMBUSTOR CONFIG: AIR-ASSIST FUEL NOZZLE	CRUISE				
	IDLE	29.8	0.6		
	APPROACH				
	CLIMBOUT				
	SLTO				
PILOTED-AIRBLAST CONCEPT CONFIG: MOD I	EPAP	10.6	.4		
	CRUISE				
	IDLE	45.1	2.5		
	APPROACH	3.9			
	CLIMBOUT				
1979 EPA STANDARDS	SLTO			14.2	--
	EPAP	10.7	.6	4.5	
	CRUISE				
	EPAP	9.4	1.6	3.7	<25

ALL VALUES COMPUTED AT ACTUAL ENGINE OPERATING CONDITIONS (STANDARD DAY).

TABLE XI. - SUMMARY OF PERFORMANCE RESULTS ACHIEVED WITH "SELECTED" ADVANCED  
TECHNOLOGY COMBUSTOR CONCEPTS FOR THE TFE 731-2 ENGINE. PRTP, PHASE I.  
PRESSURE DROP,  $\Delta p/p$ , SAME AS BASELINE FOR ALL CONCEPTS

CONFIGURATION	OPERATING CONDITION	COMBUSTION EFF. %	EXIT TEMP PATTERN FACTOR, $\frac{T_{MAX} - T_{AVE}}{T_{AVE} - T_{IN}}$
TFE731-2 ENGINE BASELINE COMBUSTOR	IDLE	97.1	
	APPROACH		
	CLIMBOUT		
	SLTO	99.9	
MODIFIED BASELINE COMBUSTOR CONFIG: AIR-ASSIST FUEL NOZZLE	IDLE	99.3	
	APPROACH		
	CLIMBOUT		
	SLTO	99.9	
PILOTED-AIRBLAST CONCEPT CONFIG: MOD I	IDLE	98.7	
	APPROACH		
	CLIMBOUT		
	SLTO	100	2 x BASELINE

ORIGINAL PAGE IS  
OF POOR QUALITY

TABLE XII. - SUMMARY OF EMISSION LEVELS ACHIEVED WITH "SELECTED" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR THE 501-D22A ENGINE. PRTP, PHASE I, VALUES AT DISCRETE OPERATING POINTS ARE IN EMISSION INDEX (E. I.)

CONFIGURATION	OPERATING CONDITION	EMISSIONS			
		CO	THC	NO <sub>x</sub>	SMOKE
501-D22A ENGINE BASELINE COMBUSTOR	IDLE	42.9	17.6	3.7	45
	APPROACH	5.1	2.0	7.5	59
	CLIMBOUT	2.0	.9	9.2	38
	SLTO	2.0	.3	8.9	37
	EPAP	31.5	15.0	6.2	59
	CRUISE				
REVERSE FLOW CONCEPT CONFIG: MOD IV	IDLE	5.1	0.2	3.9	3
	APPROACH	2.6	.3	5.8	16
	CLIMBOUT	1.1	.2	10.8	13
	SLTO	1.1	.1	11.0	17
	EPAP	4.6	.3	7.3	17
	CRUISE				
PRECHAMBER CONCEPT CONFIG: MOD III	IDLE	1.6	0.4	3.5	1
	APPROACH	3.1	.2	3.6	1
	CLIMBOUT	.9	.1	17.7	1
	SLTO	.8	.1	19.0	1
	EPAP	2.1	.4	8.5	1
	CRUISE			----	
STAGED FUEL CONCEPT CONFIG: MOD IV	IDLE	10.2	0.2	4.6	3
	APPROACH	1.9	.5	9.2	2
	CLIMBOUT	2.4	.5	9.2	4
	SLTO	1.7	.1	9.3	--
	EPAP	8.4	.4	8.1	4
	CRUISE				
EPA 1979 STANDARDS	EPAP	26.8	4.9	12.9	22

\*ALL VALUES COMPUTED AT ACTUAL ENGINE OPERATING CONDITIONS (STANDARD DAY).

TABLE XIII. - SUMMARY OF PERFORMANCE RESULTS ACHIEVED WITH "SELECTED" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR THE 501-D22A ENGINE. PRTP, PHASE I.  
PRESSURE DROP,  $\Delta p/p$ , SAME AS BASELINE FOR ALL CONCEPTS

CONFIGURATION	OPERATING CONDITION	COMBUSTION EFF, %	EXIT TEMP PATTERN FACTOR, $\frac{T_{MAX} - T_{AVE}}{T_{AVE} - T_{IN}}$
501-D22 ENGINE BASELINE COMBUSTOR	IDLE	97.4	
	APPROACH	99.7	
	CLIMBOUT	99.8	
	SLTO	99.9	
REVERSE FLOW CONCEPT CONFIG: MOD IV	IDLE	99.8	
	APPROACH	99.9	
	CLIMBOUT	99.9	0.6 x BASELINE
	SLTO	99.9	0.6 x BASELINE
PRECHAMBER CONCEPT CONFIG: MOD III	IDLE	99.9	
	APPROACH	99.9	
	CLIMBOUT	99.9	0.75 x BASELINE
	SLTO	99.9	0.7 x BASELINE
STAGED FUEL CONCEPT CONFIG: MOD IV	IDLE	99.7	
	APPROACH	99.8	
	CLIMBOUT	99.8	
	SLTO	99.9	SAME AS BASELINE 0.7 x BASELINE

ORIGINAL PAGE IS  
OF POOR QUALITY

TABLE XIV. - SUMMARY OF EMISSION LEVELS (EPAP VALUES) ACHIEVED WITH THE "BEST" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR ALL ENGINES CONSIDERED IN THE ECCP AND PRTP. ALL EPAP VALUES COMPUTED FOR ACTUAL ENGINE OPERATING CONDITIONS (STANDARD DAY)

EMISSIONS ENGINES	CO			THC			NO <sub>x</sub>		
	CONV COMB.	ADV TECH	EPA STD'S	CONV COMB.	ADV TECH	EPA STD'S	CONV COMB.	ADV TECH	EPA STD'S
CF6-50 ENGINE (DOUBLE ANNULAR CONCEPT)	10.8	3.0	4.3	4.3	0.3	0.8	7.7	4.2	3.0
JT9D-7 ENGINE (VORBITX CONCEPT)	14.3	*6.3	4.3	5.3	0.6	0.8	4.9	3.5	3.0
JT8D-17 ENGINE (VORBITX CONCEPT)	16.1	*9.0	4.3	4.4	0.2	0.8	8.2	4.3	3.0
TFE731-2 ENGINE (PILOTED-AIRBLAST CONCEPT)	17.5	*10.7	9.4	5.3	0.6	1.6	5.3	**4.5	3.7
501-D22A ENGINE (REVERSE FLOW CONCEPT)	31.5	4.6	26.8	15.0	0.3	4.9	6.2	7.3	12.9

SMOKE REQUIREMENTS SHOULD BE ACHIEVABLE FOR ALL CONCEPTS

\* LOWER VALUES EXPECTED WITH FURTHER DEVELOPMENT.

\*\*PRELIMINARY VALUE.

TABLE XV. - COMPARISON OF APPLICABLE CYCLE PARAMETERS FOR ALL ENGINES CONSIDERED IN THE ECCP AND PRTP

ENGINE	IDLE		SLTO	
	COMB. INLET PRESS. (P3), ATM	**COMB. INLET TEMP (T3), K	COMB. INLET PRESS. (P3), ATM	**COMB. INLET TEMP (T3), K
CF6-50	2.92	430	29.8	825
JT9D-7	3.95***	465***	21.2	765
JT8D-17	2.85	412	17.4	715
TFE731-2	1.95	365	13.6	688
501-D22A	3.6	440	9.7	640

\*MANUFACTURER'S RECOMMENDED POWER SETTINGS.

\*\*STANDARD DAY CONDITIONS.

\*\*\*IDLE #2, REF. 18



TABLE XVI. - QUALITATIVE COMPARISON OF THE ESTIMATED EMISSION REDUCTION POTENTIAL AND APPLICATION DIFFICULTY FOR SELECTED CONTROL TECHNIQUES EVALUATED IN NASA PROGRAMS

EMISSION CONTROL TECHNIQUE	EMISSION REDUCTION POTENTIAL	ENGINE APPLICATION DIFFICULTY	ESTIMATED IMPLEMENTATION TIME
AIR-ASSIST FUEL INJECTION (MOD BASELINE COMBS.) (REVERSE FLOW CONCEPT)	GOOD FOR CO & THC N/A FOR NO <sub>x</sub>	MINOR MODIFICATION ** (LOW DEVEL RISK)	2-3 YR
AIR BLAST FUEL ATOMIZATION (MOD BASELINE COMBS.) (PILOTED-AIRBLAST CONCEPT) PILOT STAGES	GOOD FOR CO & THC SMALL FOR NO <sub>x</sub>	MODERATE MODIFICATION (LOW DEVEL RISK)	2-3 YR
QUICK QUENCHING (MAIN STAGES)	N/A FOR CO & THC MODERATE FOR NO <sub>x</sub>	MODERATE MODIFICATION (LOW TO MODERATE DEVEL RISK)	2-3 YR
LEAN COMBUSTION (MAIN STAGES)	N/A FOR CO & THC GOOD FOR NO <sub>x</sub>	MODERATE MODIFICATION (LOW TO MODERATE DEVEL RISK)	2-3 YR
WATER INJECTION (MOD BASELINE COMB.)	N/A FOR CO & THC VERY GOOD FOR NO <sub>x</sub>	MODERATE MODIFICATION (LOW TO MODERATE DEVEL RISK)	2-3 YR
STAGED COMBUSTION (DOUBLE ANNULAR CONCEPT) (VORBIX CONCEPT)	GOOD FOR CO & THC GOOD FOR NO <sub>x</sub>	MAJOR MODIFICATION (MODERATE TO HIGH DEVEL RISK)	3-5 YR
PREVAP PREMIX COMBUSTION (FUNDAMENTAL TESTS)	EXCELLENT FOR CO & THC EXCELLENT FOR NO <sub>x</sub>	VERY MAJOR MODIFICATION (VERY HIGH DEVEL RISK)	BEYOND 1985

\* FROM DATE OF SUCCESSFUL COMPLETION OF FULL-SCALE ENGINE DEMO TEST.

\*\* DEVELOPMENT RISK IS DEFINED AS THE ABILITY TO CONVERT A DEMONSTRATED EXPERIMENTAL TECHNIQUE INTO A SATISFACTORY ENGINE COMBUSTOR.

TABLE XVII. - SUMMARY OF PERFORMANCE RESULTS FOR THE "BEST" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR ALL ENGINES CONSIDERED IN THE ECCP AND PRTP

ENGINE (CONFIG)	OPERATING CONDITION	COMBUSTION EFF	EXIT TEMP PATTERN FACTOR
CF6-50 ENGINE (DOUBLE ANNULAR CONCEPT)	IDLE	99.3	
	APPROACH	99.9	
	CLIMBOUT	100	1.5 x BASELINE
	SLTO	100	1.5 x BASELINE
JT9D-7 ENGINE (VORBIX CONCEPT)	IDLE	99.0	
	APPROACH	99.8	
	CLIMBOUT	100	1.5 x BASELINE
	SLTO	99.6	1.5 x BASELINE
JT8D-17 ENGINE (VORBIX CONCEPT)	IDLE	99.5	
	APPROACH	99.9	
	CLIMBOUT	99.8	1.7 x BASELINE
	SLTO	99.8	1.7 x BASELINE
TFE731-2 ENGINE (PILOTED-AIRBLAST CONCEPT)	IDLE	98.7	
	APPROACH		
	CLIMBOUT		
	SLTO	100	2 x BASELINE
501-D22A ENGINE (REVERSE FLOW CONCEPT)	IDLE	99.8	
	APPROACH	99.9	
	CLIMBOUT	99.9	0.6 x BASELINE
	SLTO	99.9	0.6 x BASELINE

IDLE #2 UNBLD REF. 18

FINAL PAGE IS  
OF POOR QUALITY

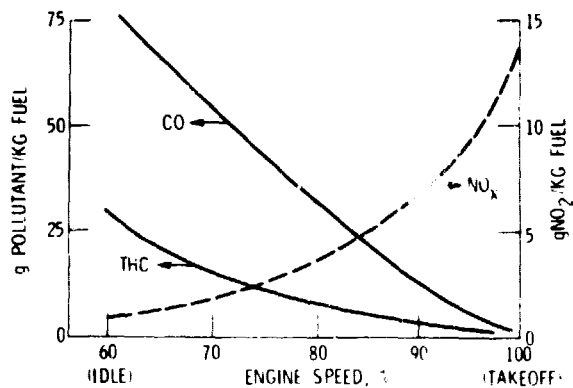


Figure 1. - Typical jet aircraft gas turbine engine exhaust emission characteristics.

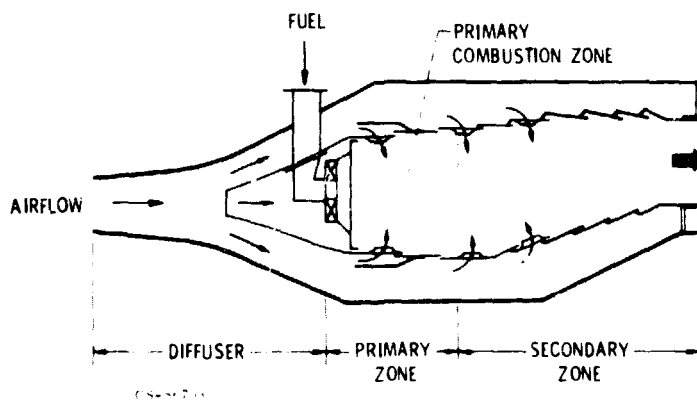


Figure 2. - Schematic illustration of a conventional annular combustor.

CONTINUED PAGE 15  
OF POOR QUALITY

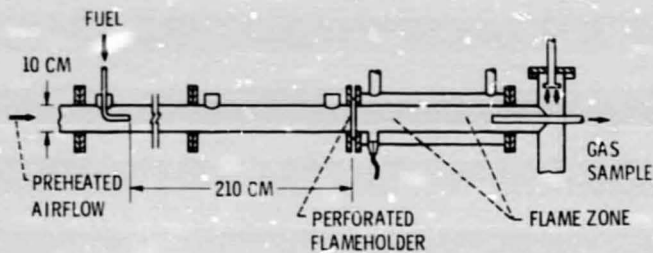


Figure 3. - Schematic illustration of the prevaporized/premixed flame tube test rig at the NASA Lewis Research Center.

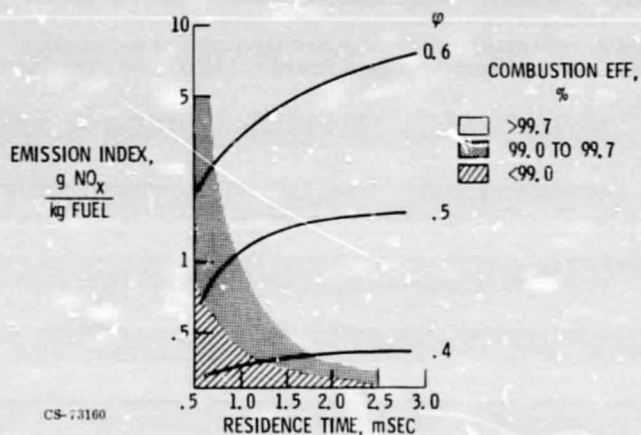


Figure 4. - Impact of combustion residence time and equivalence ratio on the formation of oxides of nitrogen and combustion efficiency in a prevaporized/premixed flame zone. Inlet pressure, 6 atms, inlet temperature, 700 K, Gaseous propane fuel.

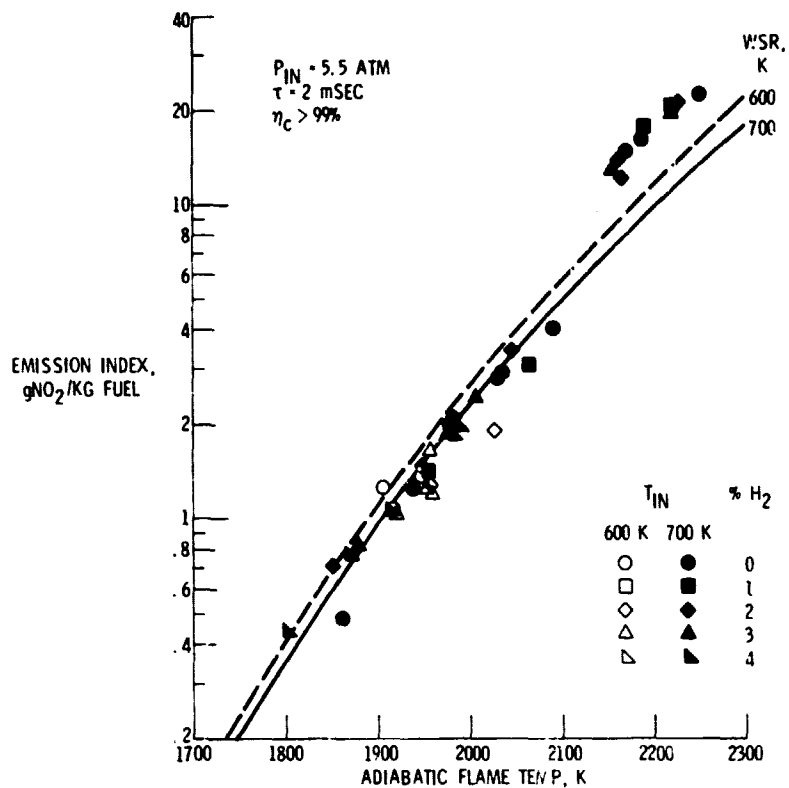


Figure 5. - Nitrogen oxides emissions from a premixed propane-hydrogen-air flame.

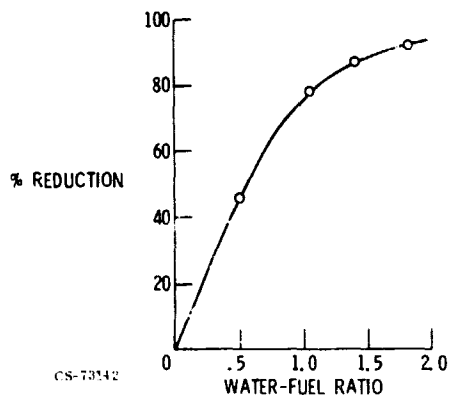


Figure 6. - Effect of water Injection on the formation of oxides of nitrogen.

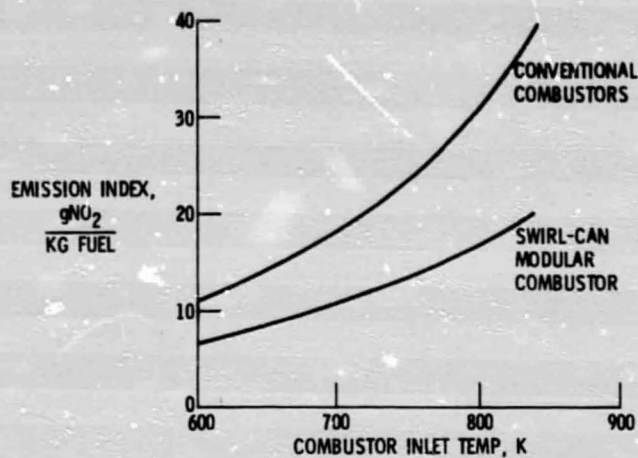
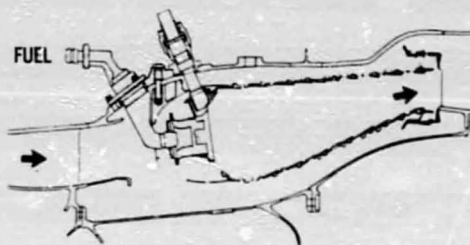
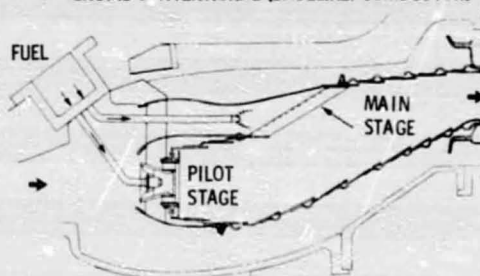


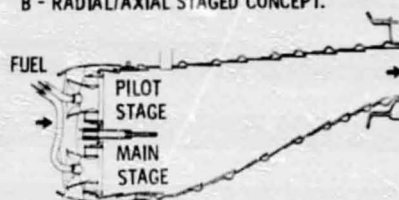
Figure 7. - Comparison of representative nitrogen oxides emission levels from conventional combustors and the experimental swirl-can modular combustor at high power (takeoff) conditions.



A - ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.

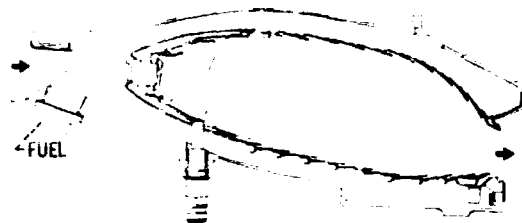


B - RADIAL/AXIAL STAGED CONCEPT.

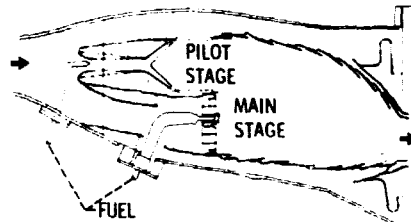


C - DOUBLE ANNULAR CONCEPT.

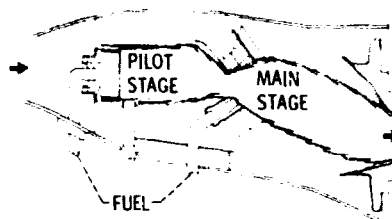
Figure 8. - Experimental clean combustor program (ECCP), Phase II advanced technology concepts for the CF6-50 engine (EPA class T2).



A - ENGINE CONVENTIONAL (BASELINE) COMBUSTOR



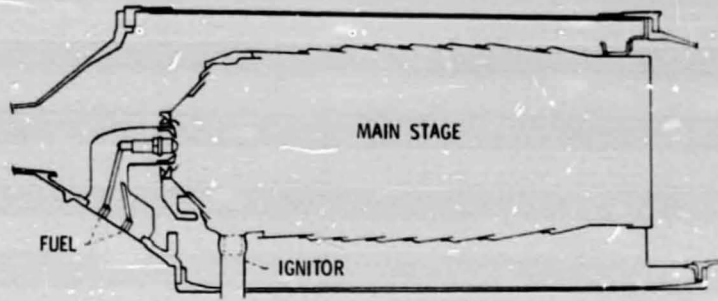
B - HYBRID CONCEPT



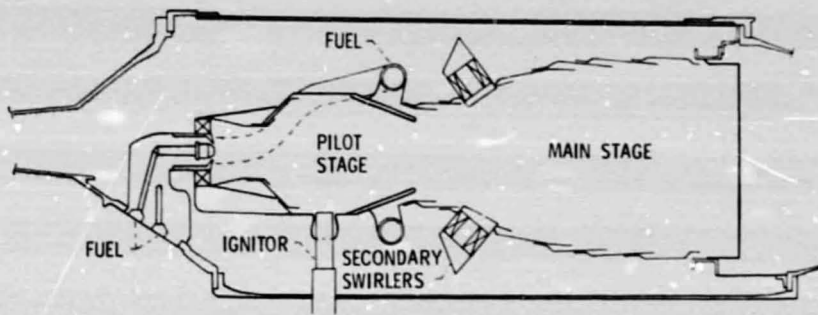
C - VORBIX CONCEPT

Figure 9. - Experimental clean combustor program (ECCP), phase II advanced technology concepts for JT9D-7 engine (EPA class T2).

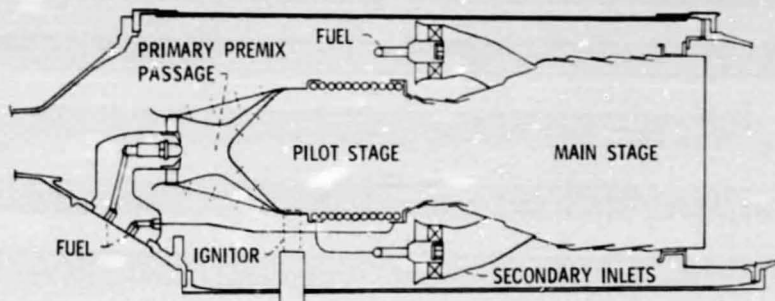
ORIGINAL PAGE IS  
OF POOR QUALITY



A - MODIFICATIONS TO ENGINE CONVENTIONAL (BASELINE) COMBUSTOR



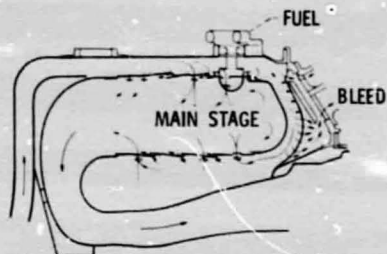
B - VORBIX CONCEPT



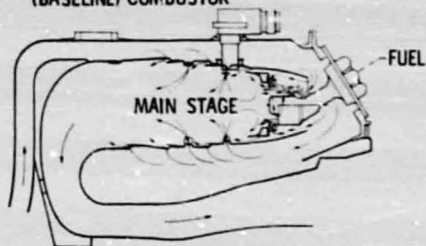
C - STAGED PREMIX CONCEPT

Figure 10. - Pollution reduction technology program (P RTP), phase I advanced technology concepts for the JT8D-17 engine (EPA class T4).

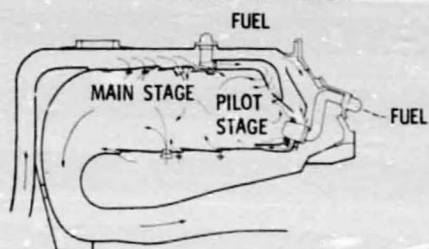
ORIGINAL PAGE IS  
OF POOR QUALITY



A - MODIFICATIONS TO ENGINE CONVENTIONAL (BASELINE) COMBUSTOR



B - PILOTED AIRBLAST CONCEPT



C - PREMIX/PREVAPORIZATION CONCEPT

Figure 11. - Pollution reduction technology program (P RTP), Phase I advanced technology concepts for the 1FE 731-2 engine (EPA class T1).

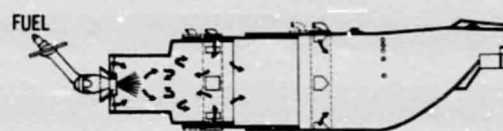




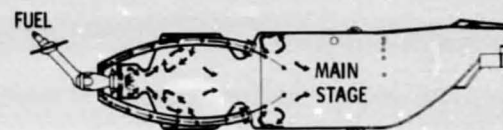
A - ENGINE CONVENTIONAL (BASELINE) COMBUSTOR



B - REVERSE FLOW CONCEPT



C - PRECHAMBER CONCEPT



D - STAGED FUEL CONCEPT

Figure 12. - Pollution reduction technology program (P RTP), phase I advanced technology concepts for the 501-D22A engine (EPA class P2).

ORIGINAL PAGE IS  
OF POOR QUALITY

# MILESTONE SCHEDULE EMISSION REDUCTION TECHNOLOGY PROGRAMS

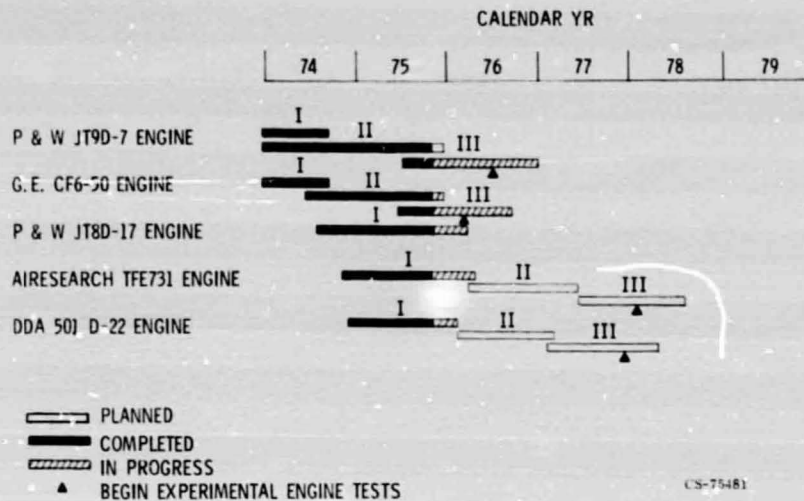


Figure 13. - Milestone schedule for NASA/industry contract emission reduction technology programs.

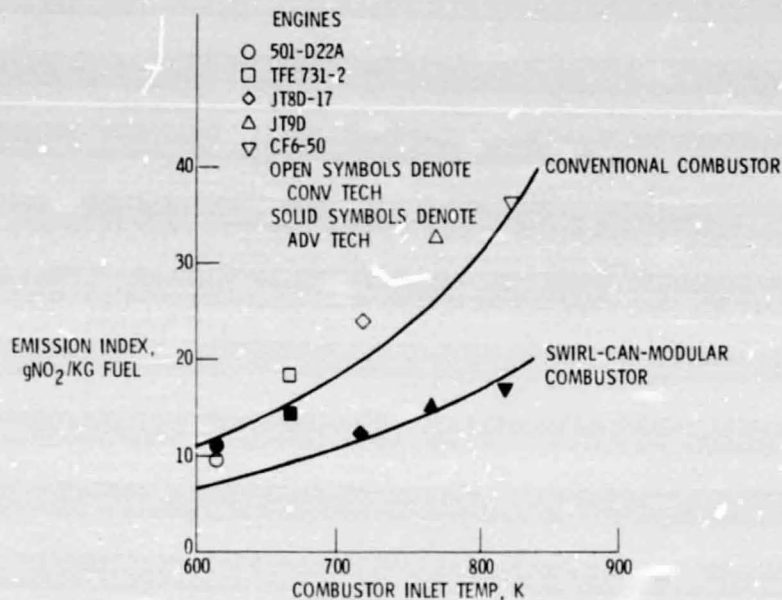


Figure 14. - Comparison of nitrogen oxides emission levels for conventional and advanced technology combustors at high power (takeoff) conditions.

ORIGINAL PAGE IS  
OF POOR QUALITY

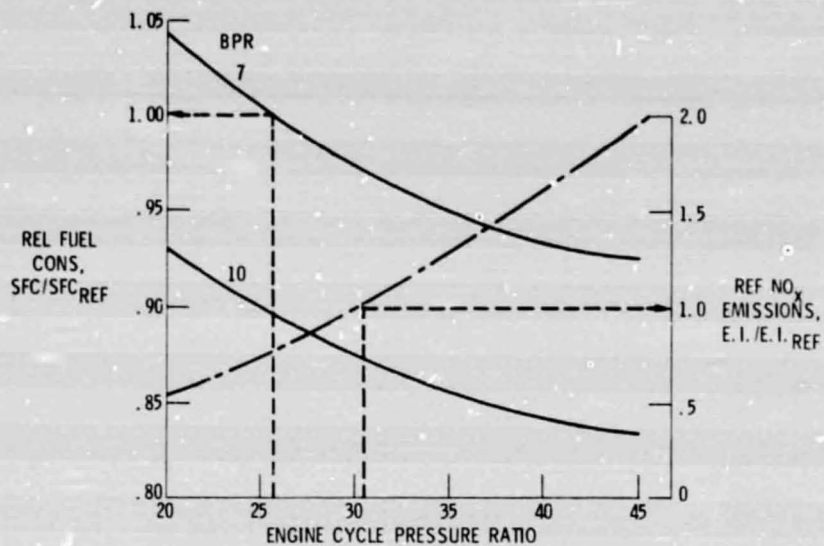


Figure 15. - Relative variations in specific fuel consumption and  $\text{NO}_x$  emissions (Eq. 1) as related to engine cycle pressure ratio and bypass ratio (ref. 23).

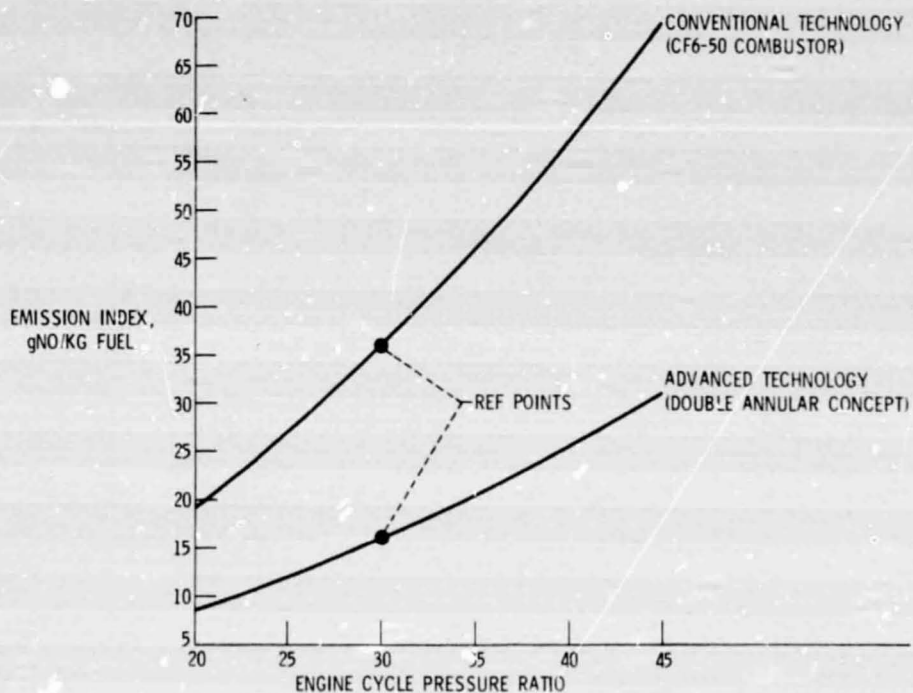


Figure 16. - Computed variation in nitrogen oxides emissions (Eq. 2) for various engine cycle pressure ratios and levels of combustor technology.